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INFLUENCES ON PIEZOMETRIC MEASUREMENTS

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

A	amplitude of water surface fluctuations
B	width of flume
C	empirical coefficient
C_h	coefficient due to hole size effect
C_T	coefficient due to total effect of intensity and scale of turbulence
d	diameter of piezometer hole
D	mean flow depth
D_r	depth indicated by reference piezometer
D_t	depth indicated by test piezometer
F	Froude number
g	acceleration of gravity
k	roughness of flume
ℓ	distance from opening in boundary to change in piezometer diameter
L	scale of turbulence
p	hydrostatic pressure
q'	resultant turbulent velocity component
Q	discharge
R	Reynolds number
R_x	correlation coefficient between values of u' along x-axis
u'	instantaneous value of velocity fluctuation in x direction
v	local mean velocity
v'	instantaneous value of velocity fluctuation in y direction

V	mean flow velocity
V_o	centerline velocity
V_t	total instantaneous velocity
x	longitudinal co-ordinate
X	longitudinal distance between points at which correlation fluctuations are measured
y	lateral co-ordinate
z	vertical co-ordinate
Δ	indicates error
γ	specific weight of fluid
μ	dynamic viscosity
ρ	fluid mass density
ν	kinematic viscosity
τ_o	fluid shear stress at boundary

SUBSCRIPTS, UNLESS DEFINED ABOVE

h	indicates value at piezometer hole
m	indicates value at manometer free surface

SUPERSCRIPTS, UNLESS DEFINED ABOVE

$\bar{}$	time average

SUMMARY

Flow depth in open channels has often been measured piezometrically. An accurate interpretation of the measurements depends upon a knowledge of the performance of the piezometer and of the characteristics of the subject being measured. The purpose of this study was to investigate the influence of boundary geometry and flow characteristics on piezometric measurement of depth in open channels for both smooth and rough boundaries.

The effect of piezometer hole diameter was studied in a smooth channel by comparing depth measurements obtained at piezometers of different diameter. Piezometer hole diameter was varied from 0.0310 to 0.3750 inch, velocity was varied from 1.44 to 7.88 feet per second, and depth was varied from 0.092 to 0.299 foot.

Roughnesses were added to the channel and a series of piezometric depth measurements, similar to those conducted in the smooth channel, were carried out. The results of these tests were compared with smooth channel data.

The effect of depth on piezometric measurements in open channels was studied by holding the velocity of flow constant and varying the depth.

Waves were mechanically generated in the test channel. The effect of surface waves on piezometrically determined depth was studied by comparing the average of the wave peaks and valleys to the quiescent pool depth.

The influence of piezometer hole diameter, channel roughness, and length of piezometer tubing on wave amplitude was investigated.

A theoretical investigation was based on an energy balance in which allowance was made for the presence of turbulent velocity fluctuations at the piezometer hole. The effects of velocity and piezometer hole diameter on the indicated pressure were shown to be functions of both scale and intensity of turbulence.

Tests results indicated that:

1. Errors in piezometric measurements of depth in smooth, open channels may be expressed as

$$\Delta D = C \frac{V^2}{g}$$

where (V) is the mean velocity and (C) is an empirical coefficient. C was shown to be a function of turbulence intensity, scale of turbulence, and piezometer hole diameter.

2. Piezometer errors were not a function of depth of flow or Froude number.

3. Boundary roughnesses served to reduce piezometric errors.

4. Surface waves did not influence piezometric depth measurements.

5. Recorded wave amplitude errors were a function of the experimental apparatus.

CHAPTER I

INTRODUCTION

Description of the Problem.--If the bottom elevation of an open channel is known, depth of flow may be readily computed by means of a piezometer when the *true static pressure is indicated*. As shown in Fig. 3 (p. 48), the depth of flow is indicated by the difference between the elevation of the free surface in the manometer (z_m) and the elevation of the piezometer hole (z_h). Flow depth is then equal to the true static pressure head (p/γ). In this study "true static pressure" was defined as the pressure which exists at a boundary when the adjacent streamlines are parallel to that boundary. Irregularities of the boundary, the measuring instrument itself, and turbulent velocity fluctuations may cause deviations from "true static pressure".

Failure to measure the true static pressure accurately may result in significant errors in depth determinations. The research section of the U.S. Geological Survey recently encountered such errors while conducting a fundamental study of open-channel flow at the Georgia Tech Hydraulics Laboratory. Discovery of these errors gave rise to this study, the purpose of which is the investigation of influences on piezometric measurements.

A piezometer is one of the basic measuring devices used by investigators in the study of fluid phenomena. Pressure drop in pipelines, pressure variations in curvilinear flow zones, loss of pressure in flow zones, loss of pressure in flow meters, depth of flow in open channels, and many other quantities are often determined by piezometric measurements.

Piezometers are obtained by drilling a hole into a boundary wall. The piezometer is then a primary element and the piezometric head (pressure plus elevation head) is indicated by a secondary instrument connected to the hole.

General Analysis of the Problem.--Pertinent quantities in an experimental study of piezometric measurements in open channels include those which describe boundary and piezometer geometry, flow characteristics, and fluid properties. Flume boundary and piezometer geometry can be described by the width of the flume (B), the flume roughness (k), the flume slope (s), the diameter of the piezometer hole (d), and the distance from the opening in the boundary to the change in piezometer diameter (ℓ). The longitudinal co-ordinate (x) was not a pertinent variable in this study since all flows were fully developed. Fluid properties can be given in terms of the mass density (ρ), the dynamic viscosity (μ), and the acceleration of gravity (g). Pertinent flow characteristics are the mean flow velocity (V), the mean flow depth (D), amplitude of water surface fluctuations (A), the resultant turbulent velocity component (q'), and the scale of turbulence (L). Thus, a statement of the error in piezometrically determined depth (ΔD) may be given by the equation

$$\Delta D = \phi (\rho , \mu , g , B , D , A , q' , L , V , d , \ell , k , s) \qquad (1)$$

Since there are fourteen variables in Equation (1), eleven dimensionless parameters may be formed:

$$\frac{\Delta D}{\frac{V^2}{2g}} = \Psi_1 \left(\frac{\rho VD}{\mu}, \frac{V}{\sqrt{gD}}, \frac{B}{D}, \frac{A}{D}, \frac{k}{D}, \frac{d}{D}, \frac{\ell}{d}, \frac{L}{d}, \frac{q'}{V}, s\right) \qquad (2)$$

The first term is a Reynolds number and the second is a Froude number. Theoretical Considerations (Chapter III) show that the depth error is proportional to the velocity head ($V^2/2g$). Therefore, a relevant dimensionless parameter is formed when the depth error is divided by the velocity head.

Scope of the Investigation.--Only sharp-edged, burr-free piezometer holes aligned normal to the boundary were considered in this investigation. A length-diameter ratio (ℓ/d) greater than two has no effect on piezometric measurements. All piezometers investigated in this study had a length-diameter ratio equal or greater than two. Experiments on piezometers with hole diameters large enough to establish an effect of d/D were not undertaken. Although two-dimensional flow probably did not exist in the test section, the effect of varying the width-depth ratio appeared insignificant for the range of boundary shear developed during this investigation.

All tests were conducted in highly turbulent flows. Thus, the effect of Reynolds number was eliminated. In open-channel flow the velocity, depth, and slope are interdependent; hence, slope is not an independent variable. Therefore, the equation of interest in this investigation is

$$\frac{\Delta D}{\frac{V^2}{2g}} = \Psi_2 \left(\frac{V}{\sqrt{gD}}, \frac{k}{D}, \frac{A}{D}, \frac{q'}{V}\right) \qquad (3)$$

CHAPTER II

REVIEW OF LITERATURE

Piezometers have been used in many instances to measure fluid pressure. The assumption was usually made that the indicated pressures were identical to the true static pressure. Henry Darcy (1), the eminent French engineer, was one of the first to propose that this assumption was not valid. He suggested, as early as 1857, that piezometers did not indicate the true static pressure, "...but this head diminished by a certain height, the diminution being due to the velocity of the fluid at the base of the piezometers: the water, by its cohesion, acts upon the manometric column, whose height it lowers."

Darcy's theory was tested experimentally by Mills (2) in 1878. Mills' experiments were carried out in a wooden flume, thirty feet long, one foot deep, and four inches wide. The velocity was varied from 0.5 to 9.0 feet per second, and the piezometer hole diameter was varied from 0.25 to 1.0 inch. Mills observed, contrary to the results predicted by Darcy, that piezometers--in the plane of the wall and aligned at right angles to the wall--indicated a depth of flow which exceeded the actual flow depth. The reported depth error was 0.225 per cent when expressed as a percentage of the mean velocity head.

Other effects noted by Mills were as follows: (a) If the tube leading from the hole was inclined upstream, the indicated pressure was increased, (b) if the tube was inclined downstream, the indicated pressure was lowered, (c) piezometers projected into the flow and inclined upstream gave large positive errors; piezometers projected normal and those projected downstream gave large negative errors, and (d) variations in piezometer hole diameter did not affect the observed pressure.

Schuster (3), in 1905, attempted to determine the piezometer edge form which would eliminate the "suction effect" of flowing water. Five piezometers were arranged 25 mm apart in the wall of a flat plate. The plate was mounted on a towing carriage and moved through still water. The range of velocities was from 2.5 to 8.4 feet per second. The resulting piezometric heads were observed in manometers which were 6.5 mm in diameter. Schuster observed negative errors which varied with velocity and piezometer edge condition. The errors associated with well-rounded edges were smallest; those associated with square-edged holes were highest. Countersunk holes yielded intermediate results.

Negative errors were also observed by Fuhrmann (4) in 1912. He attempted to determine the effect of hole size on piezometric measurements. His tests were conducted on a body of revolution placed in a wind tunnel. The hole size was varied from 0.1 to 1.1 mm and the mean velocity of the air was 32 feet per second. The errors were negative and a slight radius of rounding tended to diminish the errors.

In 1915, Gibson (5) investigated abnormal coefficients of discharge of Venturi meters. Explanations for these coefficients were proposed. Two of the explanations pertained to action of the manometric column when it was subjected to pulsating flow and to variations in the geometry of the piezometer hole.

Gibson suggested the following equation of motion for the fluid in the manometer:

$$h + \frac{v^2}{2g} + \frac{l d^2 h}{g dt^2} + \mu' \frac{dh}{dt} = \text{constant} \tag{4}$$

where h = recorded head at the throat of the meter

v = velocity in the throat

l = length of recording column

μ' = resistance coefficient

$\frac{dh}{dt}$ = velocity of flow in the column

g = acceleration due to gravity

Imposing a simple harmonic motion,

$$v = \bar{v}\,(1 + K \cos pt) \ , \tag{5}$$

Gibson solved Equation (4) subject to the conditions imposed by Equation (5) and from the solution concluded that "the mean value of h is less than that corresponding to constant flow with the mean velocity $\bar{v}$ in the ratio $1 + \frac{K^2}{2} : 1$..."

The piezometers in the throat of the Venturi meter were connected to a circumferential gap. The experiments showed that the width of the gap had some effect on the measured pressure. Gibson likewise found increases in pressure with higher velocities.

While studying pressure drops in pipe lines, Hermann (6) investigated the influence of hole size on piezometric measurements. He found, in general, positive errors which increased with hole size. Only piezometers with a small length-diameter ratio and a large chamber behind the hole showed negative errors.

Allen and Hooper (7) conducted an extensive piezometric investigation in 1932. Their objectives were "(1) to determine a stable type of piezometer suitable for use as a standard in commercial work, and (2) to determine those factors which have the greatest bearing in obtaining correct results."

Allen and Hooper conducted their experiments in a 12-inch diameter pipe carrying water with a velocity range of 4.0 to 7.2 feet per second. The hole diameter range was 0.063 to 0.688 inch. Their pertinent conclusions were: (a) Piezometric error was not a function of hole diameter, (b) piezometric error was a constant percentage of the local velocity head, (c) length-diameter ratio should be greater than two, (d) a small radius of rounding of the piezometer edge did not influence the pressure measurements, (e) a large radius gave positive errors, (f) the effect of adding rows of tubercles upstream from the piezometer was a reduction of the error; 1/4-inch mesh laid in the test section gave similar results, and (g) burrs, projections, and misalignments caused the largest errors.

Large negative errors were observed by Angus (8) when a piezometer was located immediately downstream from a misalignment of pipe flanges. Angus experimented in a 6-inch pipe with 1/8-inch holes having edge roundings of 1/16-inch.

Myadzu (9) found that piezometric errors, if expressed as a percentage of the mean velocity head, increased linearly with hole size and that the errors were not dependent on ℓ/d provided this ratio was greater than two. Myadzu conducted his experiments in a square conduit with 27 mm sides. Piezometer hole diameters were varied from 0.004 to 0.157 inch.

The influence of different wall roughness patterns was investigated by Polzin (10) in 1939. The study included tests at both smooth and rough walls. This systematic investigation is the only study of its kind known to the writer. Various grades of sandpaper were attached to the walls of a square test conduit. The test section was 2.8 meters long and had 10 cm sides. The range of sandpaper was varied from 120 to 30 mesh. This investigator suggested that these roughnesses corresponded to the roughnesses found in commercial pipes and that sandpaper could thus be used as a satisfactory means of scaling roughness.

As a result of Polzin's investigation, it was concluded that for smooth walls (a) negative errors were produced, (b) errors increased with conduit Reynolds number, (c) burr-free, sharp-edged holes were most desirable, and (d) the size of the errors was largely influenced by the edge shape of the piezometer.

Polzin concluded that, for rough walls,

(a) on an average, errors were not larger than those at smooth walls,

(b) large roughnesses were more favorable because they were less subject to other influences, such as burrs, etc.,

(c) the numerical magnitude of the errors was approximately the same as those at smooth walls,

(d) with favorable arrangement of roughnesses, the error was approximately one per cent of the center line stagnation head, or 1.4 per cent of the stagnation head based on the mean stream velocity,

(e) distribution of roughnesses was more significant than absolute size of roughness (this appeared more true for small roughnesses than for large),

(f) roughnesses in front of a hole caused negative errors which were nearly proportional to the Reynolds number,

(g) roughness behind a hole caused a stagnation action and the error appeared to be independent of Reynolds number,

(h) a definite relation between hole size and error was not apparent, and

(i) in forming a piezometer hole, the edge shape was more important in the case of small roughnesses as compared to piezometers near large roughnesses.

Fluid compressibility, a phenomenon not investigated in earlier water experiments, was investigated by Rayle (11) in 1949. He studied piezometric error as a function of Mach number, hole diameter, and hole edge shape. Both water and air were used. The respective velocity ranges were 22 to 31 feet per second and 400 to 900 feet per second. A one-inch diameter test section was located downstream from a nozzle. Piezometer diameters were varied from 0.006 to 0.125 inch. Rayle found positive errors which increased with diameter and Mach number. A countersunk hole tended to decrease the error while a rounding of the hole edge increased the error.

Ray (12) attempted a theoretical study of the effect of hole size on piezometric measurements. By considering the laws of similitude and by assuming linear velocity distribution close to the boundary, Ray derived the following expression for the pressure error, Δp :

$$\Delta p = \frac{\rho V^2}{2} f(R_e , \ \ell/d) \tag{6}$$

When ℓ/d was held constant and equal to unity and when $R_e = \frac{d^2}{\nu}\frac{dv}{dy}$, his experimental results were represented by

$$\Delta p = 0.29\ d^{1/2}\ \tau^{5/4}\ \mu^{-1/2}\ {}^{1/4} \tag{7}$$

where τ is the fluid shear stress.

From photographic studies in a glass pot of 48 mm diameter he concluded that

$$\Delta p = \frac{\rho V^2}{2}\ c \tag{8}$$

where
$$V_c = f(R_e)\ V_1$$
$$f(R_e) = 0.58\ R_e^{-3/4}$$
$$V_1 = d\ \frac{dv}{dy}$$

A velocity of five cm per second was used in the photographic study.

Shaw (13) extended the range of previous work on pressure measurements in incompressible turbulent flow. For piezometers of constant ℓ/d value, Shaw showed that the relationship which expressed his results was

$$\frac{\Delta p}{\tau_o} = f(R_e) \tag{9}$$

where $R_e = \frac{dU_*}{\nu}$, τ_o was the fluid shear stress at a boundary, U_* was $\sqrt{\tau_o/\rho}$, and ν was kinematic viscosity.

Shaw's experiments were carried out with air flowing in a two-inch diameter pipe. Velocities were varied from 38 to 212 feet per second and hole size was varied from 0.016 to 0.189 inch. Positive errors were reported and these errors increased with hole diameter and velocity. A single curve was drawn to express the error as a function of a Reynolds number when the length-diameter ratio was equal to or greater than 1.5.

Hooper (14) studied piezometric depth measurements in an open channel. Five piezometers were located on the bottom and three piezometers were located on each side of a flume at a section five feet from the downstream end. The tilting flume was 22 feet long, 12 inches wide, and 12 inches deep. All piezometers were one-eighth inch in diameter and were made up in brass plugs and set into the flume walls. Construction of the piezometers followed recommendations set forth earlier by Allen and Hooper. Velocities were varied from 3.0 to 7.0 feet per second. Errors were expressed as a percentage of the velocity head. Hooper fould errors of 0.8 per cent of the mean velocity head.

A systematic study of piezometric errors in open channels was conducted by Emmett (15). Water was flowing. A test section containing 24 piezometers was located at the downstream end of a smooth, rectangular flume which was 22 feet long, 10 inches wide, and 18 inches deep. Piezometer hole diameters were varied from 0.031 to 0.375 inch; channel slope was varied from 0.00291 to 0.0349. The range of depth was 0.084 to 0.173 foot, and Froude number range was 0.70 to 3.50. Emmett reported that the error for a given piezometer hole diameter was a function of the mean velocity head. All errors were positive and increased with hole diameter, depth of flow, and Froude number.

The effect of surface waves was considered by Emmett, but no definite conclusions were reached. This particular aspect of Emmett's investigation is extended by the writer in this thesis.

In 1936, the first publications which dealt with the effect of turbulent velocity fluctuations on static pressure measurements appeared. Goldstein (16) presented a theoretical analysis of this phenomenon. He proposed that the measured mean static pressure, p_m , should be given by

$$p_m = p + c \rho q' \tag{10}$$

where p = true static pressure

c = empirical coefficient

ρ = mass density

q' = resultant turbulent component of velocity

Goldstein suggested that the constant, c , could be determined by experiment, and that the value of this constant would probably lie between zero and one-third. This analysis was made for static pressure tubes.

By employing measurements previously made with an ultramicroscope, Fage (17) determined experimentally the value of the coefficient suggested by Goldstein. Fage concluded that,

> The relationship between the reading of a static pressure tube (S) and the true average static pressure $(\overline{p})$ is expressed in the form
>
> $$S = \overline{p} + K \left(\overline{v^2} + \overline{w^2}\right) \tag{11}$$
>
> where v and w are the cross components of the turbulent velocity, and K has a characteristic value for the same tube in turbulent streams of the same kind.

As usual, the barred values denoted time averages. Fage found the value of K for fully developed turbulent flow in pipes to be approximately

0.25.

In 1960, Landweber (18) presented a theoretical analysis of the influence of turbulent velocity fluctuations. The analysis was concerned with corrections of velocity profiles obtained with Pitot tubes. Corrections for this effect were given in graphical form.

Alexander, Baron, and Comings (19) found that, contrary to their expectations, the pressure indicated by a total head tube decreased as the turbulence intensity increased. Turbulence intensity was defined by the ratio of the root mean square value of the turbulent velocity component to the mean velocity. Their results were based on total head measurements taken at various distances downstream from a grid placed in front of a nozzle.

Other authors who have suggested that turbulent velocity fluctuations influence static pressure measurements include Kalinske (20), Hubbard (21), Nielson (22), Folsom (23), and Hinze (24).

Dorrestein (25) considered a prism in an inviscid fluid moving under the influence of gravity. He analyzed a momentum balance and developed the following equation:

$$\bar{p} = \gamma(\bar{h} - z) - \rho\overline{w^2} \tag{12}$$

where z = fixed level of point considered, P

$\bar{h}$ = average level of fluid surface

$\bar{p}$ = pressure at point P

ρ = mass density

$\overline{w^2}$ = mean square vertical velocity at P

Dorrestein suggested that this equation would apply to an "arbitrary steady and horizontally homogeneous turbulent motion."

Kalinshe (26), White (27), and Howe (28) suggested that variations of the flow resistance in the manometer and its connections may cause piezometric errors if the flow is of a pulsating nature. Hubbard (29) tried to determine the error due to dynamic effects of manometer pulsations. His test results indicated that there was no observable error caused by dynamic forces.

The purpose of the writer's study was to investigate the influence of boundary geometry and flow characteristics on piezometric measurement of depth in open channels. Effects due to (a) piezometer hole diameter, (b) flow depth, (c) channel roughness, (d) surface waves, and (e) fluid turbulence were considered.

CHAPTER III

THEORETICAL CONSIDERATIONS

Inviscid and Laminar Flow.--If streamlines adjacent to a piezometer hole are parallel to the boundary, true static pressure can be measured with a piezometer. Deviations from parallel configurations are expected in the vicinity of boundary irregularities. Deviations occur even if the flow is inviscid. A typical flow pattern of a piezometer for an inviscid fluid is shown in Fig. 1. Pressure at the hole is greater than the true static pressure due to altered streamline spacing.

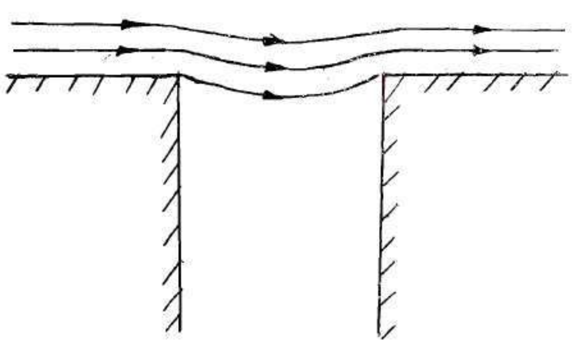


Fig. 1. Typical Inviscid Flow Pattern at a Piezometer

Increased pressures in inviscid flow have been computed theoretically (11). However, fluids are not inviscid and fluid viscosity causes flow patterns to vary from those predicted by inviscid theory. As fluid particles move past a piezometer hole, viscous shear forces act on the fluid within the hole and motion is imparted to the fluid in the hole as a result of these shear forces. Flow within the hole is characterized by eddying motion.

For flow at very low Reynolds numbers piezometric errors have been determined analytically (13).

Turbulent Flow.--As flow is increased, it will eventually become unstable and turbulence will result. Turbulent velocity fluctuations will alter the laminar flow pattern near a piezometer as described above. Turbulent flows near channel walls have been investigated by Laufer (30), Klebanoff (31), and others. These investigations have shown that turbulent velocity fluctuations become zero at solid boundaries. However, a piezometer allows a degree of freedom and the resultant component of turbulent velocity does not disappear at a piezometer hole.

By analyzing an equation of motion, the effect of turbulent fluctuations may be predicted. An equation of motion is

$$\frac{1}{g}\frac{\partial V_t}{\partial t} = -\frac{\partial}{\partial s}\left[\frac{p}{\gamma} + z + \frac{V_t^{\,2}}{2g}\right] \tag{13}$$

where V_t is the total instantaneous velocity, p the hydrostatic pressure, z the elevation, γ the specific weight of the fluid, and viscosity is neglected.

When the total velocity is replaced by the mean velocity plus the fluctuation component $(v + q')$, Equation (13) becomes

$$\frac{1}{g}\frac{\partial}{\partial t}\left[v + q'\right] = -\frac{\partial}{\partial s}\left[\frac{p}{\gamma} + z + \frac{v^2 + 2\,vq' + q'^2}{2g}\right] \tag{14}$$

Integration of Equation (14) along a streamline for steady flow yields

$$\frac{1}{g}\int\frac{\partial q'}{\partial t}\,ds = -\left[\frac{p}{\gamma} + z + \frac{v^2 + 2\,vq' + q'^2}{2g}\right] + \text{constant} \qquad (15)$$

The terms in Equation (15), when averaged over a period of time, become

$$\overline{\frac{1}{g}\int\frac{\partial q'}{\partial t}\,ds} = -\left[\frac{\bar{p}}{\gamma} + \bar{z} + \frac{\bar{v}^2 + \overline{2\,vq'} + \overline{q'}^2}{2g}\right] + \text{constant} \qquad (16)$$

where the bar denotes time averages.

Taken over an appropriately long time interval

$$\overline{\frac{1}{g}\int\frac{\partial q'}{\partial t}\,ds} = \frac{1}{g}\int\overline{\frac{\partial q'}{\partial t}}\,ds = \frac{1}{g}\int\frac{\partial\overline{q'}}{\partial t}\,ds = 0 \qquad (17)$$

and

$$\overline{vq'} = v\overline{q'} = 0 \qquad (18)$$

Therefore,

$$\frac{\bar{p}}{\gamma} + \bar{z} + \frac{\bar{v}^2}{2g} + \frac{\overline{q'}^2}{2g} = \text{constant} \qquad (19)$$

Equation (19) is an energy equation for steady turbulent flow. The energy balance between the fluid at the piezometer hole and the fluid in the manometer is

$$\frac{\bar{p}_h}{\gamma} + \bar{z}_h + \frac{\overline{v^2}_h}{2g} + \frac{\overline{q'^2}_h}{2g} = \frac{\bar{p}_m}{\gamma} + \bar{z}_m + \frac{\overline{v^2}_m}{2g} + \frac{\overline{q'^2}_m}{2g} \qquad (20)$$

where the subscript h denotes fluid at the hole and m denotes fluid at the free surface of the manometer. At the hole

$$\frac{\overline{v_h^{\,2}}}{2g} = 0 \tag{21}$$

At the free surface

$$\frac{\bar{p}_m}{\gamma} = 0 = \frac{\overline{v_m^{\,2}}}{2g} = \frac{\overline{q'^{\,2}_h}}{2g} \tag{22}$$

Therefore, flow depth indicated by a manometer is

$$\bar{z}_m - \bar{z}_h = \frac{\bar{p}_h}{\gamma} + \frac{\overline{q'^{\,2}_h}}{2g} \tag{23}$$

Hence, a flow depth indicated by a manometer is greater than that indicated by hydrostatic pressure alone. This error in depth measurement is due to turbulent fluctuations and may be expressed as

$$\triangle D_T = \frac{\overline{q'^{\,2}_h}}{2g} \tag{24}$$

A non-dimensional error is formed by dividing Equation (24) by the mean velocity head.

$$\frac{\triangle D_T}{\frac{V^2}{2g}} = \frac{\frac{\overline{q'^{\,2}}}{2g}}{\frac{V^2}{2g}} = \frac{\overline{q'^{\,2}}}{V^2} \tag{25}$$

A characteristic measurement of turbulence intensity is $\sqrt{\overline{q'^{\,2}}}$.
Hence, the non-dimensional error is given in terms of the squared value

of the turbulence intensity.

Fluid turbulence is characterized not only by intensity, but also by scale of turbulence. Therefore, errors in depth measurements will depend on scale of turbulence as well as on turbulence intensity. The scale of turbulence corresponding to correlations along the x-axis is denoted by

$$L_x \equiv \int_0^\infty R_x \, dX \tag{26}$$

where R_x is a correlation coefficient between velocity fluctuations in direction of mean flow, and X represents distances between points at which correlation fluctuations are measured.

When a piezometer hole is very much smaller than the scale of turbulence, only a small per cent of the energy contained in the turbulent fluctuations will have an effect on the piezometer. A piezometer hole approximately the same size as the scale of turbulence will not restrain the influence of turbulence. Piezometer holes larger than the scale of turbulence will not be subject to increased effects.

Accordingly, for given turbulence characteristics, the size of piezometer hole will affect piezometric measurements. The influence of hole size can be introduced by altering Equation (24) to read

$$\Delta D_T = C_h \frac{\overline{q'^2_h}}{2g} \tag{27}$$

where C_h is an experimentally determined coefficient.

Turbulent velocity fluctuations for flow in smooth channels have been shown to be a percentage of the mean stream velocity (30, 31). Thus, the depth error may be expressed as

$$\Delta D_T = C_T \frac{V^2}{g} \tag{28}$$

where C_T includes the total effect of intensity and scale of turbulence. As described above, the coefficient, C_T, will reach a maximum value when a piezometer hole is large enough to allow the full influence of turbulent velocity fluctuations.

Boundary roughnesses affect the scale and intensity of turbulence. Therefore, piezometrically measured depths in open channel flow will vary with wall roughness. In general, the effects depend on (a) flow velocity, (b) geometry of roughness, and (c) location of roughnesses relative to the piezometer hole.

Surface Waves.--Piezometric measurements in open channels are influenced by the varying pressure gradient under surface waves. Pressure under wave peaks is higher than pressure under valleys. Fluid particles subjected to reversed pressure gradients will experience acceleration and deceleration as a wave passes, as shown in Fig. 2.

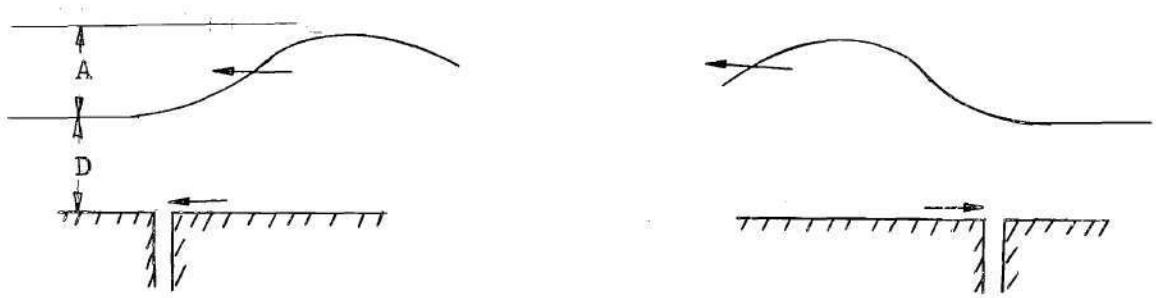


Fig. 2. Surface Waves

The pressure gradient under a given wave is described by the amplitude-depth ratio (A/D).

Different boundary conditions on opposite sides of the piezometer hole will cause the flow patterns on opposing sides to be different. Hence, boundary roughnesses may be a source of error in piezometric measurements of surface waves.

Piezometers that offer resistance to flow in one direction which is different from that in the other are often constructed. Pulsating flow in such a piezometer will encounter greater energy losses in one direction than in the other. Surface waves cause flow in a piezometer to be of a pulsating nature and, therefore, may introduce errors in piezometric measurements.

CHAPTER IV

EQUIPMENT AND INSTRUMENTATION

General Arrangement.--This experimental investigation was carried out in the Hydraulics Laboratory, School of Civil Engineering, and in the Low Turbulence Wind Tunnel, Daniel Guggenheim School of Aeronautics, Georgia Institute of Technology. The piezometer test section was located in a tilting flume located in the Hydraulics Laboratory. Existing hot-wire equipment in the Low Turbulence Wind Tunnel was employed for turbulence measurements. The arrangement of the experimental equipment is shown in Fig. 4 and 5.

The Flume.--A water-carrying flume was used in this investigation. This flume was 22 feet long, 18 inches deep, and 10 inches wide. It was supplied with water through a six-inch pipeline connected to the laboratory's re-circulating constant-head system. The water entered the channel through a diffuser and straightening vanes located in the forebay of the flume. The water surface profiles were controlled by an adjustable sluice gate at the entrance to the channel and by an adjustable tailgate. The flume slope was varied from 0.01746 to 0.03929 by means of an electrically operated jack at the downstream end. The flume pivoted under the forebay.

The Piezometer Test Section.--Considerable care was used in aligning the test section. This section was located at the downstream end of the flume. The floor of the test section was made of stainless steel.

Twenty-four piezometers in the test section were arranged in eight groups of three piezometers each. A group included one test piezometer and two reference piezometers. The piezometers in each group were 0.1 foot apart transverse to the direction of flow. Each group of piezometers was located 0.2 foot downstream from the preceding group. The last group was located 1.85 feet upstream from the tailgate. Sizes of test piezometers varied from 0.031 to 0.375 inch in diameter. All but the smallest piezometer were drilled directly into the floor of the test section. The 0.031 inch piezometer was drilled into a brass plug. The plug was subsequently tapped into and finished flush with the floor of the test section. The length-diameter ratio of all piezometers was constant and equal to three ($\ell/d = 3$). One-quarter inch I.D. copper tubes connected each of the piezometers to a dial-type manifold. These leads were made of equal length. The piezometer connections are illustrated in Fig. 7. Figure 6 shows details of the test section. Table 1 gives a summary of the piezometric openings.

Discharge Measurements.--Rates of discharges were measured either by a bend meter or gravimetrically. Flows greater than 0.5 cubic feet per second were measured by the bend meter in the six-inch supply line. Smaller discharges were measured gravimetrically. The weighing apparatus is shown in Fig. 4a.

The Wave Generator.--A plunger-type surface wave generator was employed in this investigation. The generator was driven by a one-quarter horsepower electric motor. A shaft with four pulleys of different diameter was turned by a belt drive connected to the electric motor. Power was then transmitted to four smaller pulleys which turned an aluminum wheel five inches in diameter. A triangular wooden plunger was linked eccentrically to the aluminum wheel by a connecting rod. Wave amplitudes were controlled by varying the eccentricity of the connection. Wave frequencies were governed by the selection of a particular set of drive pulleys. The wave generator is shown in Fig. 8.

Effective wave reflection was prevented by the installation of a wave dissipator at the downstream end of the flume. The dissipator was in the form of a permeable sloping beach and was made of a fibrous sponge.

Piezometric Measurements.--The piezometric head at any piezometer located in the open channel test section was indicated by two secondary instruments, a constant displacement manometer and a transducer connected to a direct-writing oscillograph.

The manometer was made from 0.175 inch I.D. glass tubing. It was back-lighted for better readability. The manometer was read just as the needle appeared to touch its reflection on the meniscus. The measurements were read to 0.001 foot.

The Statham transducer had a pressure range of ± 0.15 psi. The pressure transducer was connected to the piezometer manifold by a one-quarter inch I.D. copper tube. The manifold and all connections were designed to allow bleeding and back flushing.

The oscillograph was a Sanborn Twin Viso Model 60.

Water Surface Measurements.--Two additional instruments for measuring the water surface elevation were available. One of these was a Neyrpic electric point gage. This gage was mounted on a carriage which could be moved longitudinally along rails at the top of the flume. Rails on the carriage permitted transverse movement of the gage. The point gage could be read accurately to the nearest 0.1 mm.

The other instrument was a capacitance-type gage designed and built in the Engineering Experiment Station of Georgia Tech. It utilized a partially submerged probe to yield an instantaneous response to variations in water surface elevations. This device was also connected to the Sanborn recorder. Although the response of this instrument was not linear, a "nearly linear" section of the calibration curve coincided with the operating range.

The electric point gage and the capacitance gage are shown in Fig. 9a and 9b, respectively. Typical calibration curves for the transducer and capacitance gage are illustrated in Fig. 10a and 10b. Simultaneous recordings of piezometric head were indicated by the transducer and capacitance gage. Typical recordings are shown in Fig. 11.

The Wind Tunnel.--An investigation of turbulence near a piezometer hole was carried out in the Low Turbulence Wind Tunnel of the Daniel Guggenheim School of Aeronautics. The permanent wind tunnel channel was 242.0 inches long, 42.0 inches wide, and 42.0 inches deep. This channel was modified so that studies of turbulence phenomena in two-dimensional flow might be performed. The modified channel, in which the writer's measurements were made, was 5.0 inches wide, 32.0 inches deep, and 30.0 feet long. The last 22.0 feet were made of one-half inch plexiglas and the preceding 8.0 feet were constructed of one-half inch plywood. Air passed from a fan section through a wide angle diffuser and a settling chamber before entering the streamlined channel entrance. A honeycomb which consisted of one-inch I.D. pipes, eight inches long, was inserted at the upstream end of the plywood section.

The tunnel was operated by a variable speed D.C. motor which drove a four-bladed fan. The speed was controlled by a rheostat. The writer's investigation was carried out at a mean centerline speed of 40.0 feet per second. The Reynolds number based on this velocity and one-half channel width was 47,500.

Turbulence Measurements.--Turbulence measurements were made with a constant-current, hot-wire anemometer. A 0.0001-inch diameter Wallaston wire of one and one-half millimeter length was soldered to the tips of sewing needles and was used to measure turbulent fluctuations. The wire was 90 per cent platinum and 10 per cent rhodium. The anemometer was mounted on a traversing mechanism at the downstream end of the channel. The mechanism permitted the hot-wire anemometer to be positioned at any desired location in the channel cross section. The tip of the probe extended a maximum of six inches into the channel.

Measurements for the purpose of this study were made of the longitudinal velocity fluctuations only.

The Test Piezometer.--A test piezometer was drilled into the plexiglas wall of the channel. The hot-wire anemometer was used to investigate the turbulence in the vicinity of this piezometer. The piezometer was of three-eighths-inch diameter. It was located 22.0 inches above the floor of the channel and four inches from the downstream end. In order to provide a length-diameter ratio of two, a plexiglas plate was attached to the wall behind the hole. The hole extended one-quarter inch into this plate. A one-quarter inch rubber tube 18.0 inches long was connected to the piezometer. The end of the tube was clamped in order to provide an air cushion behind the piezometer and thus to simulate the action of a manometer.

CHAPTER V

EXPERIMENTAL PROCEDURE AND RESULTS

Scope of the Tests.--The experimental program for this study consisted essentially of four series of tests. The first series was designed to verify conclusions drawn from a previous investigation, made at the Georgia Institute of Technology, on piezometric measurements in smooth, open channels (15). In the second series, roughnesses were added to the floor of the water channel. The test results were to be compared with smooth channel data. The third series was conducted to establish the effect of surface waves on piezometrically determined depth. Finally, the fourth series was performed in a wind tunnel to determine the magnitude of the turbulent velocity fluctuations in the vicinity of a wall piezometer.

Smooth Channel Tests.--Prior to each test, the manifold, manometer, and connections were bled and backflushed to eliminate errors due to impurities and entrapped air. The capacitance gage was calibrated and the transducer bridge balanced. The method used to determine uniform flow depth consisted of point-gage measurements at seven longitudinal stations. The flow was considered uniform when depth measurements yielded identical results at all stations. Uniform flow depth was established by regulating the sluice gate or tailgate.

The discharge and channel slope were recorded for each test. Test conditions are described in Table 2.

At each of the eight groups of piezometers, the water surface elevation was measured with the electric point-gage. The point-gage was read when the indicator light appeared to be lit 50 per cent of the time. A mean flow depth was computed by averaging all point-gage measurements.

Water surface fluctuations were measured with the capacitance gage. Fluctuations of the capacitance gage oscillograph record were averaged by a fitted straight line.

The piezometric heads indicated by the manometer and by the transducer at each of the 24 piezometers were recorded. The manometer fluctuations were averaged and the mean value recorded. The valve to the manometer was kept closed during all transducer recordings since an open manometer dampened the transducer signal. A straight line was fitted to average the random fluctuations recorded by the transducer oscillograph.

Relative piezometric error, the difference in the piezometric head indicated by the test piezometer (D_t) and that indicated by the reference piezometer (D_r), was expressed as

$$\Delta D = D_t - D_r \tag{29}$$

The results of three tests to determine hole size effect are illustrated by Fig. 12. Emmett (14) had presented depth errors as a percentage of the mean velocity head and expressed all of his test results by a single curve. This curve is shown as a solid line on Fig. 12.

Effect of flow depth on piezometric measurements was studied by holding the velocity constant and varying the depth. On Fig. 13a and 13b the results of these tests are shown.

Rough Channel Tests.--One-half inch hardware cloth, placed on the flume floor, was used as boundary roughness. A single strand of piano wire prevented the cloth from being washed downstream. One end of the wire was connected to the upstream end of the flume; the other end was attached to the hardware cloth. The length of this wire was adjusted to various distances in order to maintain similar approach conditions for the groups of piezometers.

Two test conditions were investigated. In the first test, the distance from the downstream edge of the cloth to each piezometer group was three-quarters inch and the roughness was 10 inches wide and 18 inches long. In the second test, the distance was 0.2 foot and the entire floor upstream from the test section was covered with cloth.

The test procedure employed for the rough channel tests was essentially the same as that for the smooth channel tests. However, the highly agitated surface associated with the rough boundary gave rise to difficulties in obtaining accurate point-gage measurements. Large discrepancies were originally noted between the flow depths determined by point-gage measurements and piezometrically determined depths. These errors were probably due to wave rideup and surface tension effects. The errors were reduced from approximately 12 per cent of the depth to less than 2 per cent by modifying the point-gage. The modification consisted of a thin (0.003 inch) triangular platelet clamped to the existing point. The mean depth was determined by averaging the elevations of crests and valleys of the water surface fluctuations.

The discharge and depth of flow were adjusted to correspond to values previously used during the smooth channel tests. Depth errors in rough channels were compared with smooth channel data. This comparison is shown graphically on Fig. 14.

Tests with Surface Waves.--A test pool was formed in the flume by sealing the tailgate and filling the flume with water to a depth of 0.3 foot. The depth of water in the quiescent pool was determined before and after each test by point-gage and piezometric measurements.

The wave generator was placed on top of the flume, seven feet from the test section. Waves of known frequency and amplitude were generated mechanically in the test flume and the recorded mean depths were compared with measurements in the quiescent pool.

Two transducers and two recorders were employed during these tests. One transducer was connected to a reference piezometer and one was connected to a test piezometer in the same group. The other reference piezometer in each group was connected to the manometer. Typical procedure for these tests involved the following operations:

1. Connecting the secondary instruments to the piezometers,
2. selecting a set of pulleys to provide the desired wave frequency,
3. varying the eccentricity of the rod connection to produce different wave amplitudes,
4. recording the maximum and minimum fluctuations of the manometer,

5. recording the varying piezometric head on transducer oscillographs,

6. measuring elevations of wave crests and valleys with the point-gage, and

7. recording water surface fluctuations with the capacitance gage.

This procedure was followed for each group of piezometers.

Waves of one and two cycles per second were generated for each of five eccentricities. The frequency of the generators was varied from one to four cycles per second, but at frequencies greater than two cycles per second the plunger merely churned the water, and wave interference made the tests unusable.

Wave amplitudes were varied from 0.005 to 0.05 foot. Average depth measurements (depths computed by averaging the maximum and minimum recorded values) were compared with quiescent pool depth (0.3 foot). Typical test data for these tests are shown in Fig. 15 and 16.

To determine the effect of boundary roughness on the piezometrically determined wave amplitude, another series of wave tests was conducted. Waves were generated and recorded in the manner previously described. Two roughnesses were used. One roughness consisted of size 36 open cut sandpaper; the other roughness was provided by rods three-sixteenths inches square and ten inches long. Arrangement of the roughnesses and wave amplitude measurements are shown in Fig. 17.

During the tests with surface waves, one transducer was located on a building column approximately 12 feet from the test section. A similar transducer was located a few inches from the test section. The transducer on the column yielded greater wave amplitudes than did the closer transducer. Subsequently, a more systematic study of this phenomenon was conducted by preparing two connecting tubes 18 and 36 inches long. Larger pressure variations were recorded when the 36-inch tube was in place. Tube length effect is shown in Fig. 18.

Wind Tunnel Tests.--Turbulence intensity measurements were made near a piezometer located in a vertical wall of the wind tunnel. Velocity fluctuations in the vicinity of the piezometer hole were measured with the hot-wire anemometer. Measurements were made by traversing the channel at four elevations. Traverses were made at 21.00, 21.50, 21.75, and 22.00 inches above the floor of the channel in the y-z plane four inches from the downstream end of the channel. Longitudinal, lateral, and vertical co-ordinates were symbolized by x , y , and z respectively.

In order to make measurements inside the piezometer hole, the hot-wire probe was inclined toward the wall. For all tests the wire was vertical in the y-z plane and was placed 90° to the mean flow direction.

Turbulence intensity measurements made in the vicinity of the piezometer hole were compared to measurements made near a smooth wall.

Mean velocity measurements close to the wall (y less than 0.25 inch) and in the piezometer hole were made with the hot-wire. Velocity measurements at greater y-distances were made with a Pitot tube. The mean velocity was computed by graphically integrating a velocity profile.

Data obtained in the wind tunnel tests are shown in Fig. 19 and 20.

CHAPTER VI

ANALYSIS AND DISCUSSION OF RESULTS

Smooth Channel Tests

<u>Influence of Hole Size</u>.--Errors relative to the reference piezometers (d_r = 0.0595 inch) were obtained as previously described and were expressed as $D_t - D_r$. It was assumed that errors in piezometric measurements approach zero as flow velocity and piezometer hole diameter approach zero. Absolute piezometric errors were obtained by extrapolating experimental results to zero diameter and by translating the error curve vertically to correspond to the assumed conditions.

Dimensional considerations indicated that errors in piezometrically determined depths are proportional to velocity head. Division of the relative errors by the velocity head and extrapolation of these non-dimensional errors to absolute values, as described above, yielded the data shown in Fig. 12.

Figure 12 illustrates the influence of piezometer hole diameter on piezometric depth measurements in open channels. Errors approached zero at small diameters. As the piezometer hole diameter increased, there was a corresponding increase in the errors. The errors increased rapidly to a piezometer diameter of approximately 0.200 inch, and then less rapidly to a diameter of 0.375 inch, which was the limit of this investigation. Thus, the experimental data followed the trend predicted by the theoretical considerations. A more thorough analysis of the influence of hole size is presented in a subsequent section of this chapter.

Only one test was run with a Froude number less than unity. This test, due to the low velocity of flow, showed no significant errors. Therefore, the results from this test are not shown on Fig. 12.

The scatter of data on Fig. 12 is of the same magnitude as was observed in a previous investigation at Georgia Tech (15). Since the same equipment was used in the present investigation, the scatter is believed to be characteristic of the experimental apparatus.

Influence of the Depth.--Effect of depth on piezometric measurements was determined by comparing data from Test 2 and 3 with results from the previous Georgia Tech investigation. To verify the conclusion that errors in piezometric depth measurements increase with depth, the writer conducted tests with flows at mean velocities comparable to Emmett's, but at greater depths. Data from these tests are shown on Fig. 13. Emmett's results are shown as a smooth line. In both tests the relative errors were the same as those reported by Emmett, even though the flow depths were twice as great. (Slightly higher errors in Test 2 were due to the use of a higher velocity than was used in the previous test.) Therefore, depth errors did not increase with depth, but only with velocity and hole size.

Re-Analysis of Previous Experimental Data.--It had been stated (15) that errors in piezometric depth measurements increase with Froude number. This conclusion was based on Fig. 21, in which piezometric errors, as a percentage of mean flow depth, are plotted against Froude number. This same data is shown plotted on log-log co-ordinates on Fig. 22. Each set of points represents a straight line with a slope of two. Therefore, the relationship between the variables can be described by the empirical equation

$$\frac{\Delta D}{D} = C\ F^{2} + K \tag{30}$$

where F is a Froude number $\left(\frac{V}{\sqrt{gD}}\right)$ and C is an empirical coefficient which has a value governed by the diameter of the piezometer. When $F = 0$, $\Delta D = 0$. Hence, Equation (30) may be written as

$$\frac{\Delta D}{D} = C \quad {}^{2} \tag{31}$$

or

$$\frac{\Delta D}{D} = C\ \frac{V^{2}}{gD} \tag{32}$$

Equation (32) is essentially the same as Equation (28), which expressed depth errors due to turbulent velocity fluctuations. Thus, it appears that the Froude number was not a significant parameter in itself, but that errors due to turbulence, when expressed as a percentage of the depth, formed a type of Froude number.

The effect of piezometer hole diameter on piezometric measurements was determined by analyzing Fig. 21 and 22. Differences in adjacent curves were large for piezometers of small diameter. For diameters greater than 0.200 inch, relatively large increases in diameter yielded only slight differences in the curves. This trend was further elucidated by Fig. 23. The coefficient increased rapidly at small diameters, but as the diameter was increased further, the corresponding increase in

C was slight. The curve eventually became vertical when C was approximately 0.009 and when the diameter was approximately 0.4 inch. This trend was predicted by the theoretical analysis of the effect of turbulence.

No measurements of scale of turbulence were made in the investigation, but previous investigators have made these measurements. Laufer (30), in an investigation of turbulent channel flow, reported a value of L_x equal to 0.437 inch. Scale of turbulence, according to Laufer, showed no consistant variation with velocity.

Measurements of turbulence intensity were made at a wall piezometer. These measurements are shown in Fig. 20. This figure shows that (a) turbulent velocity fluctuations existed at a piezometer hole, (b) turbulence intensity at the hole was of a significant magnitude, and (c) turbulent velocity fluctuations in the vicinity of the hole were not appreciably altered by the hole. Turbulence intensity measurements made during this investigation compare favorably to results previously reported (30).

In the case of turbulence which is roughly isotropic

$$\overline{u'^2} \simeq \overline{v'^2} \simeq \overline{w'^2} \tag{33}$$

where u' , v' , and w' are instantaneous values of velocity fluctuations in the x , y , and z directions, respectively.

Then

$$q' = \sqrt{\overline{u'^2} + \overline{v'^2} + \overline{w'^2}} \tag{34}$$

The value of $\sqrt{\frac{\overline{u'^2}}{V}}$ at the piezometer hole was 0.08.

Therefore,

$$\frac{\overline{u'^2}}{V^2} = 0.0064 \tag{35}$$

or

$$\overline{u'^2} = 0.0064V^2 \tag{36}$$

and furthermore,

$$\overline{q'} = \sqrt{3(0.0064V^2)} \tag{37}$$

and

$$\overline{q'^2} = 0.0192V^2 \tag{38}$$

Thus, the largest theoretical error due to turbulence may be expressed by

$$\Delta D_{max} = \frac{q_h'}{2g} = \frac{0.0192V^2}{2g} = 0.0096\ \frac{V^2}{g} \tag{39}$$

Equation (39), divided by the depth D , is shown as a dotted line on Fig. 21. Thus, Equation (39) expresses piezometric depth errors obtained when the effect of turbulence is not restrained by the hole. The plot of Equation (39) corresponded to a piezometer hole diameter of approximately 0.45 inch. Scale of turbulence given above was 0.437 inch. Agreement of these values, hole size and the scale of turbulence, was predicted by theoretical considerations.

Comparison with Results of Other Investigations.--Variations in experimental equipment and procedure made a direct comparison with many of the previous investigations impossible. Nevertheless, some data from earlier investigations have shown trends similar to those established in this thesis. The study reported by Hooper (14) was the only comparable open channel investigation. The error reported by Hooper (0.7 per cent of mean velocity head at one-eighth inch piezometers) compared favorably with errors found in the Georgia Tech studies (approximately 0.8 per cent).

Equation (1) was used to compare results obtained at Georgia Tech with results obtained by Ray (12). Ray's equation yielded errors two to three times larger. Since Ray extrapolated results which were obtained with slowly moving water and a large glass pot, doubts arise as to the validity of his results when applied to high flow velocities and small piezometers.

Shaw (13) reported that, for a constant length-diameter ratio, errors were only a function of a Reynolds number. However, some of his data showed variations of more than 30 per cent from his average curve. This curve is shown on Fig. 24. Data from the present study compared favorably with Shaw's average curve at high velocities and low Raynolds numbers. Figure 24 shows this comparison. If Shaw had drawn his average curve through points representing the mean value of his data, his curve would have corresponded more closely to the writer's data. In all cases Shaw's empirical curves showed a trend similar to that determined by the present investigation.

Rayle's (11) errors, when analyzed in the same manner as Shaw's, were of an equivalent magnitude and followed the same trend as the Georgia Tech data. Rayle's results are shown as a dotted line on Fig. 24.

Even though Myadzu (9) reported errors which increased linearly with hole size, the magnitude of the errors was approximately equal to those found at Georgia Tech. This comparison is shown on Fig. 25.

Rough Channel Tests

Results of tests carried out to determine the effect of channel roughnesses on piezometric depth measurements are shown on Fig. 14. Flow depths and discharges corresponded to values recorded during smooth channel tests. Magnitude of errors found in rough channel tests were approximately one-half to two-thirds the value of errors found in smooth channels.

Infinite variations in possible boundary roughnesses precluded a theoretical discussion of boundary roughness effects at this time. Discovery of specific information on the effect of roughnesses on scale and intensity of turbulence was not within the scope of this investigation.

Since only a very limited range of roughnesses and of roughness spacing was investigated, no generalization on the effect of roughness can be made. The reader is referred to the work of Polzin (10) for an example of results which may be obtained in an investigation of roughness effects.

Surface Wave Tests

Waves generated during these tests were sinusoidal in nature.

Typical wave patterns recorded on the capacitance gage and transducer oscillographs are shown on Fig. 26. Effective wave reflections were prevented by the wave dissipator. Wave reflections with and without the dissipator in place are shown in Fig. 27. The first peak represents the generated wave, the second peak represents the reflection from the tailgate, and the third peak represents the wave after it had been reflected from the forebay.

The average water surface elevation (average of wave peaks and valleys) was compared to the quiescent pool depth. Measurements made with the manometer, transducer, and capacitance gage showed the average depth with waves present to be equal to the quiescent pool depth. Typical results are shown on Fig. 15. All measurements made with the unaltered point-gage showed positive errors. This trend was due to surface tension effects.

Effect of different boundary conditions on opposite sides of a piezometer hole was investigated. The results are shown on Fig. 17. Such conditions were found to have no effect on recorded wave amplitudes.

Oscillograph records of solitary waves recorded with two different length of piezometer tubes are shown on Fig. 28. These records were made with both the transducer and capacitance gage oscillographs. One tube leading to the transducer was 17 feet long; the other was four inches long. Large secondary oscillations with a period of 0.7 seconds were in evidence on the transducer record when the long tube was used. There was a time lag of about 0.1 seconds in the transducer record. The short tube yielded a water surface profile similar to that recorded by the capacitance gage.

With a tube 12 feet long in place, the time lag was reduced to 0.05 seconds, and the period of oscillation was reduced to 0.55 seconds.

Tube length also had an effect on recorded wave amplitude, as is shown on Fig. 18. A build-up in pressure due to a reinforcement of primary pressure patterns by oscillations in the tube is a possible explanation for these variations.

Effect of piezometer hole diameter on recorded wave amplitude was tested. No effect of hole diameter was in evidence. Typical data are shown on Fig. 16.

CHAPTER VII

CONCLUSIONS

1. Errors in piezometric measurements of depth in smooth, open channels may be expressed as a function of mean velocity and piezometer hole diameter.

2. Experiments in channel flow have substantiated the error equation

$$\Delta D = C \frac{V^2}{g} \tag{28}$$

where (V) is the mean velocity and (C) is an empirical coefficient. C was shown to be a function of turbulence intensity, scale of turbulence, and piezometer hole diameter.

3. Piezometric errors were not a function of depth or Froude number.

4. Boundary roughnesses, which consisted of one-half inch hardware cloth placed upstream from the piezometer tests section, served to reduce errors in piezometric measurement of depth.

5. Effects of boundary roughnesses on intensity and scale of turbulence must be elucidated in future research before a thorough analysis of the effect in turbulence of piezometric measurements in rough channels may be advanced.

6. Recorded wave amplitude was a function of the experimental apparatus used in the measurements. When wave amplitude was measured

with a pressure transducer, the recorded amplitude was a function of the length of tubing which connected the piezometer hole to the transducer.

7. Recorded wave amplitude was not a function of piezometer hole diameter.

8. Piezometrically measured wave amplitude was not a function of boundary roughness.

9. For the limited conditions investigated in this study, surface waves did not influence piezometric depth measurements.

APPENDIX

Table 1. Summary of Piezometer Openings

Piezometer Number	Piezometer Section	Piezometer Diameter (Inches)	Remarks
1	1	0.0310	(1),(2)
2	1	0.0595	(3)
3	1	0.0595	(4)
4	2	0.0595	(2)
5	2	0.0595	(3)
6	2	0.0595	(4)
7	3	0.0935	(2)
8	3	0.0595	(3)
9	3	0.0595	(4)
10	4	0.1200	(2)
11	4	0.0595	(3)
12	4	0.0595	(4)
13	5	0.1562	(2)
14	5	0.0595	(3)
15	5	0.0595	(4)
16	6	0.1850	(2)
17	6	0.0595	(3)
18	6	0.0595	(4)
19	7	0.2500	(2)
20	7	0.0595	(3)
21	7	0.0595	(4)
22	8	0.3750	(2)
23	8	0.0595	(3)
24	8	0.0595	(4)

(1) Drilled into brass plug.
(2) Test piezometer.
(3) Centerline reference piezometer.
(4) Outer reference piezometer.

Table 2. Flow Data, Open Channel Tests

Test No.	Q cfs	D ft.	S ft/ft	V fps
1	0.364	0.092	0.0262	4.77
2	1.490	0.277	0.0279	7.88
3	1.732	0.299	0.0175	6.95
4	0.331	0.276	0.0018	1.44
5*	0.872	0.176	0.0393	6.66
6*	0.892	0.206	0.0349	5.21

*rough channel tests

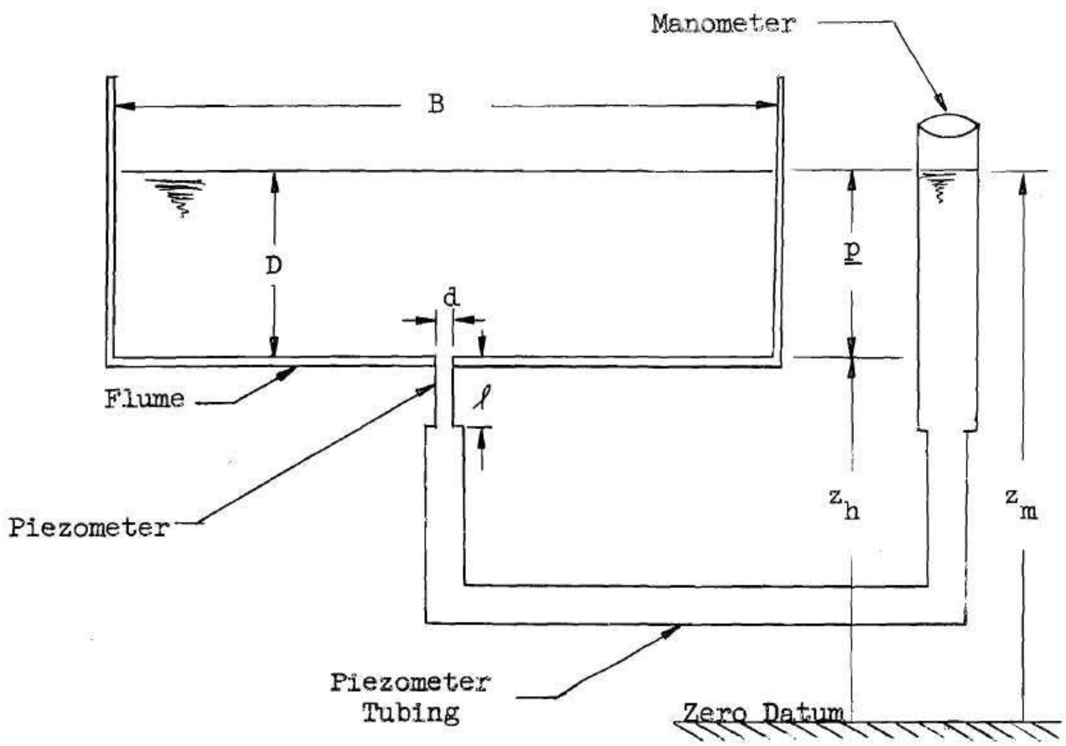
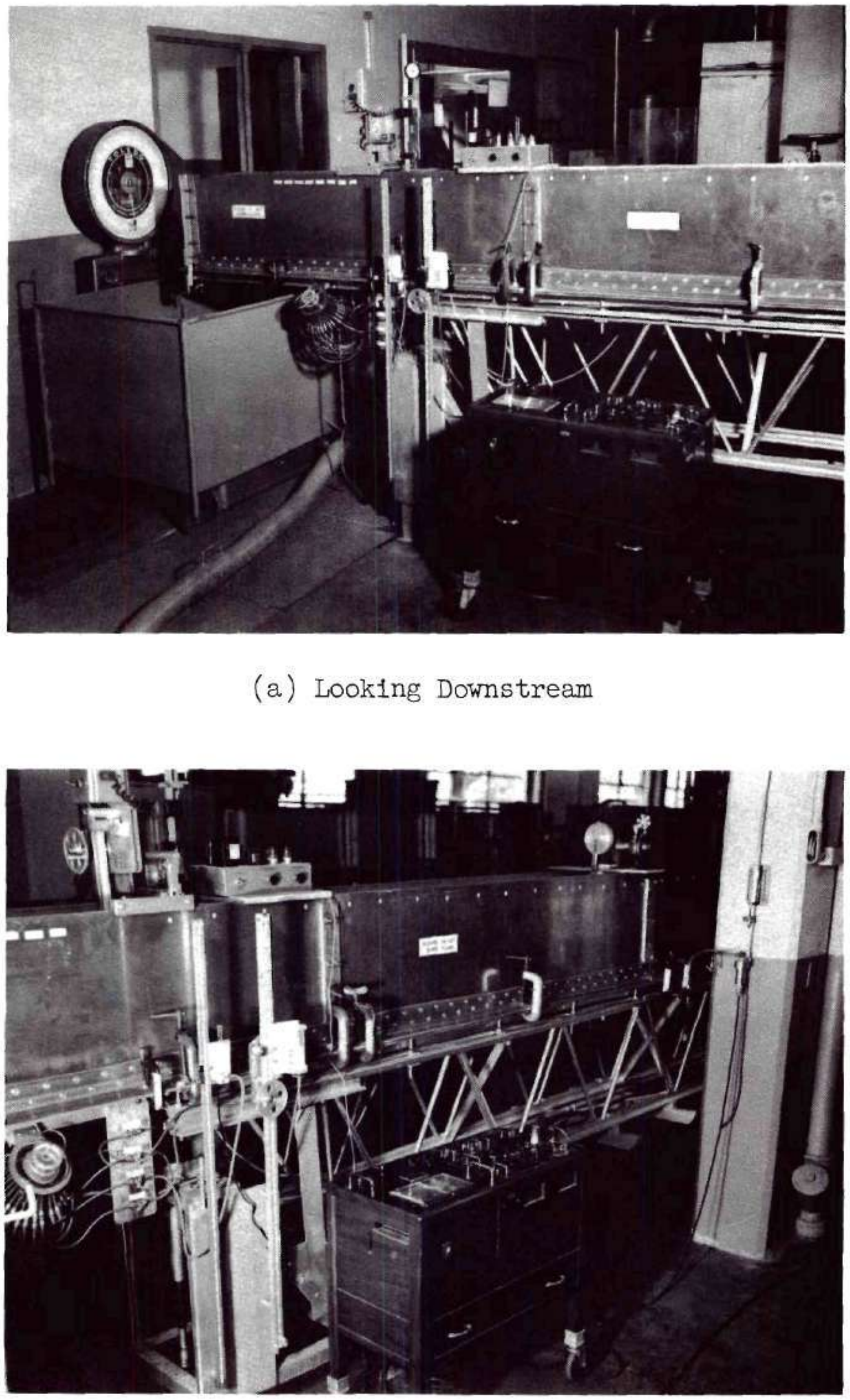


Fig. 3. Piezometric Depth Determination



(a) Looking Downstream

(b) Looking Upstream

Figure 4. Arrangement of Experimental Apparatus.

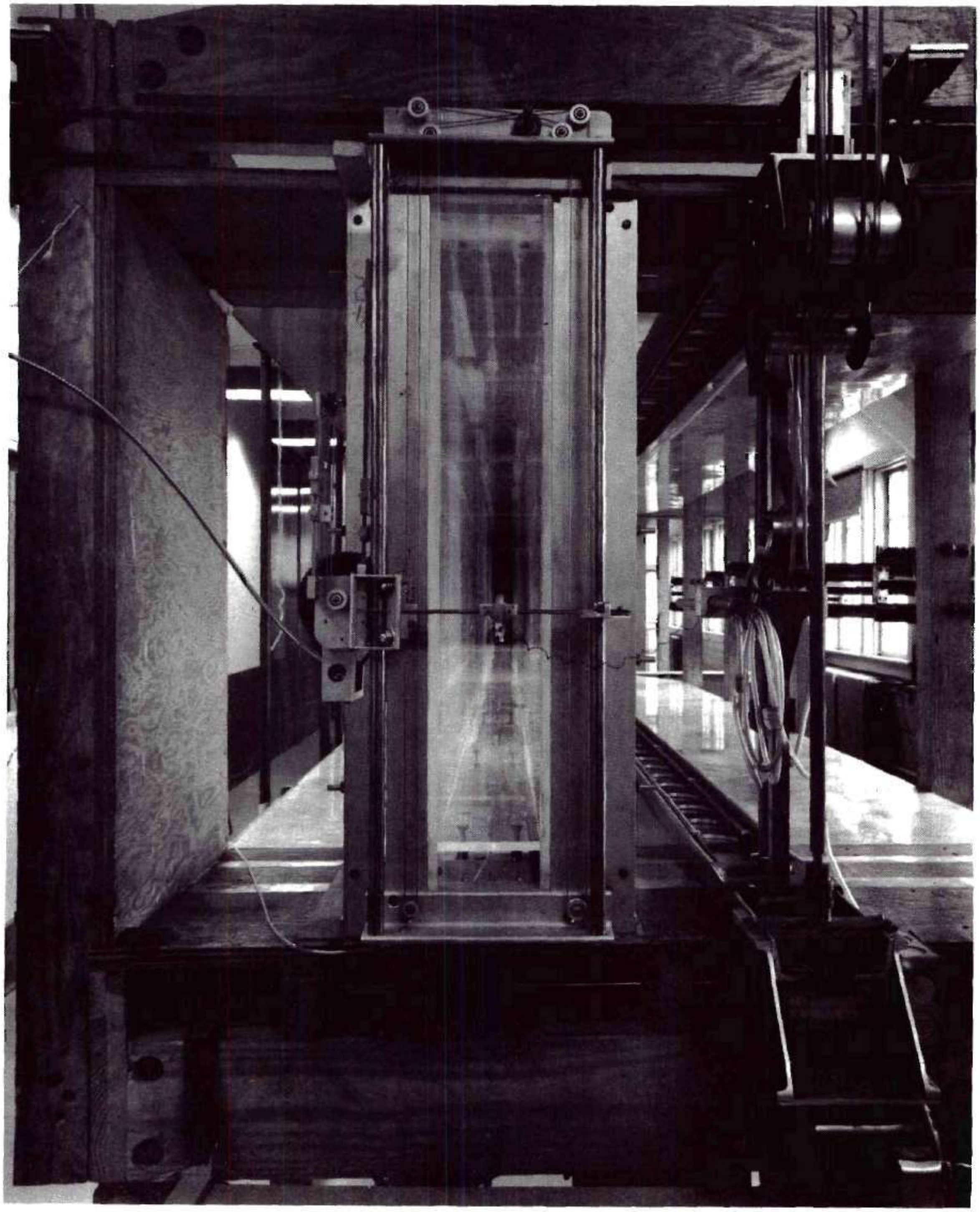
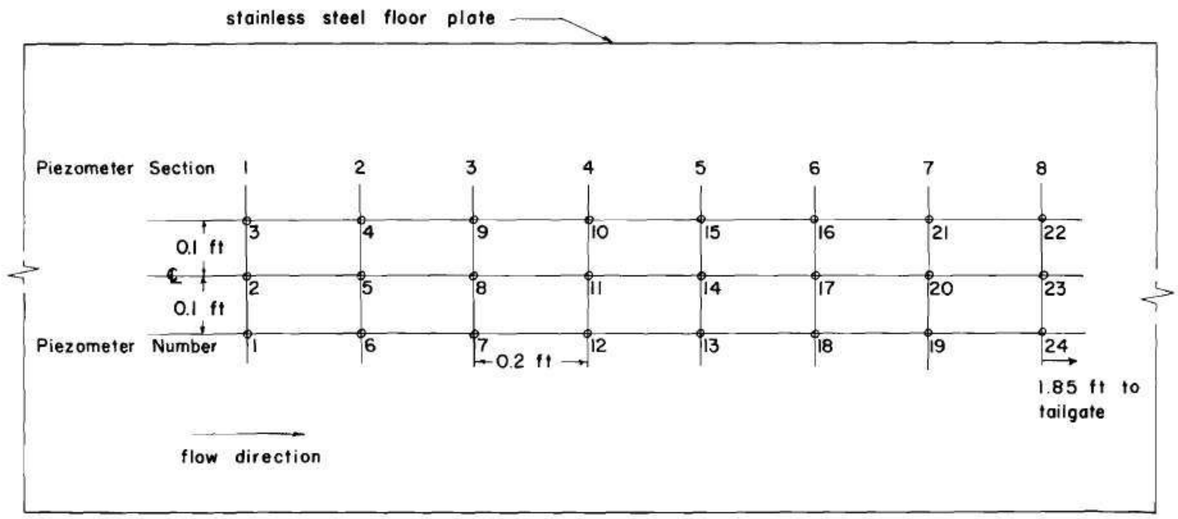
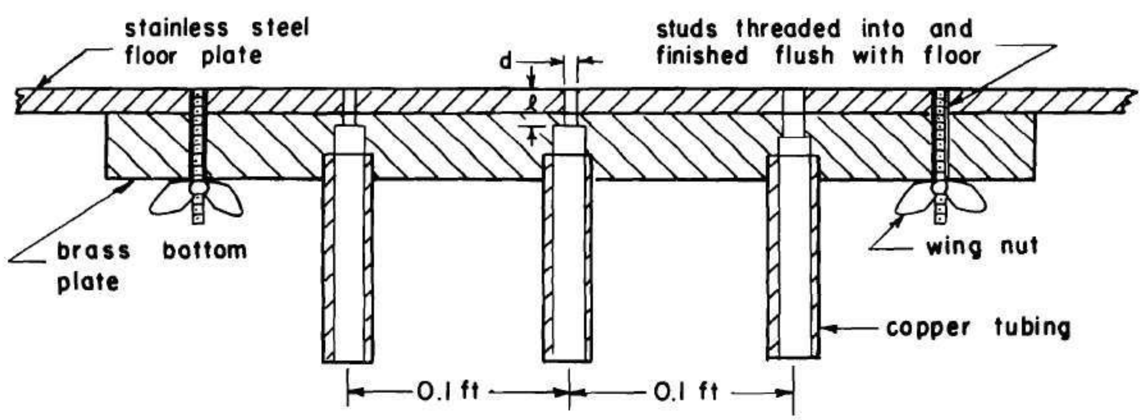


Figure 5. Downstream End of Wind Tunnel.

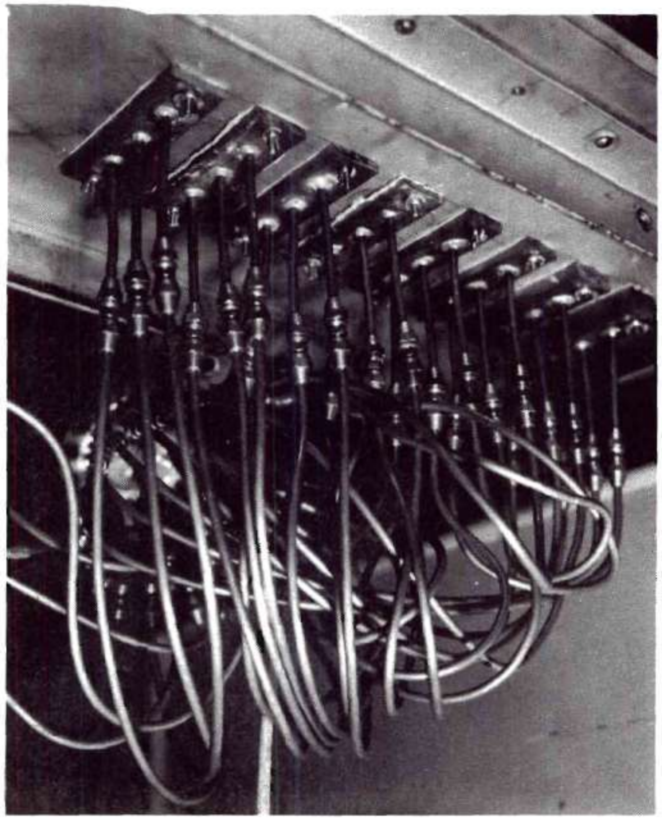


(a) Plan View of Piezometer Test Section.

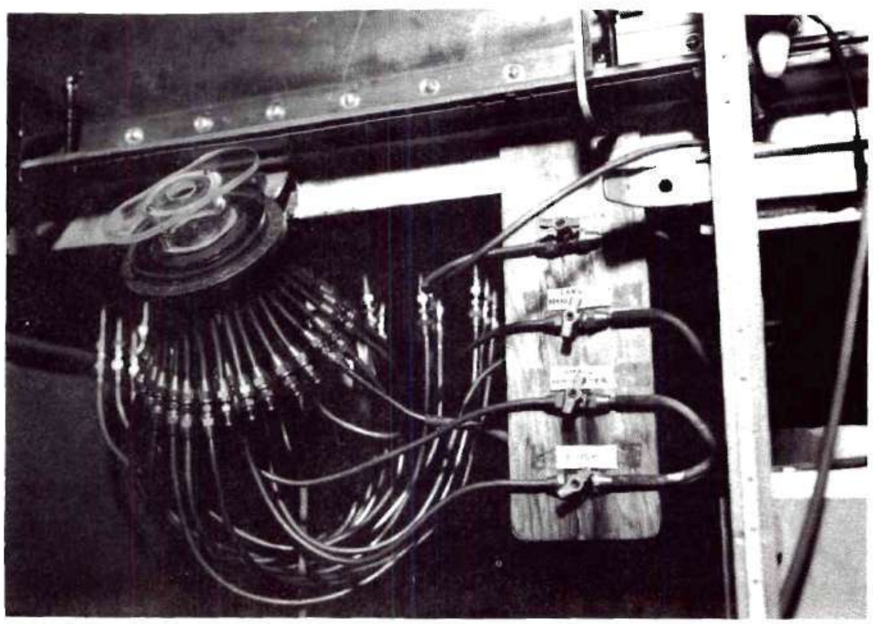


(b) Typical Cross-Section of Piezometer Openings.

Figure 6. Open Channel Test Sections.



(a) Bottom View of Test Section



(b) Dial-Type Manifold

Figure 7. Piezometer Connections.

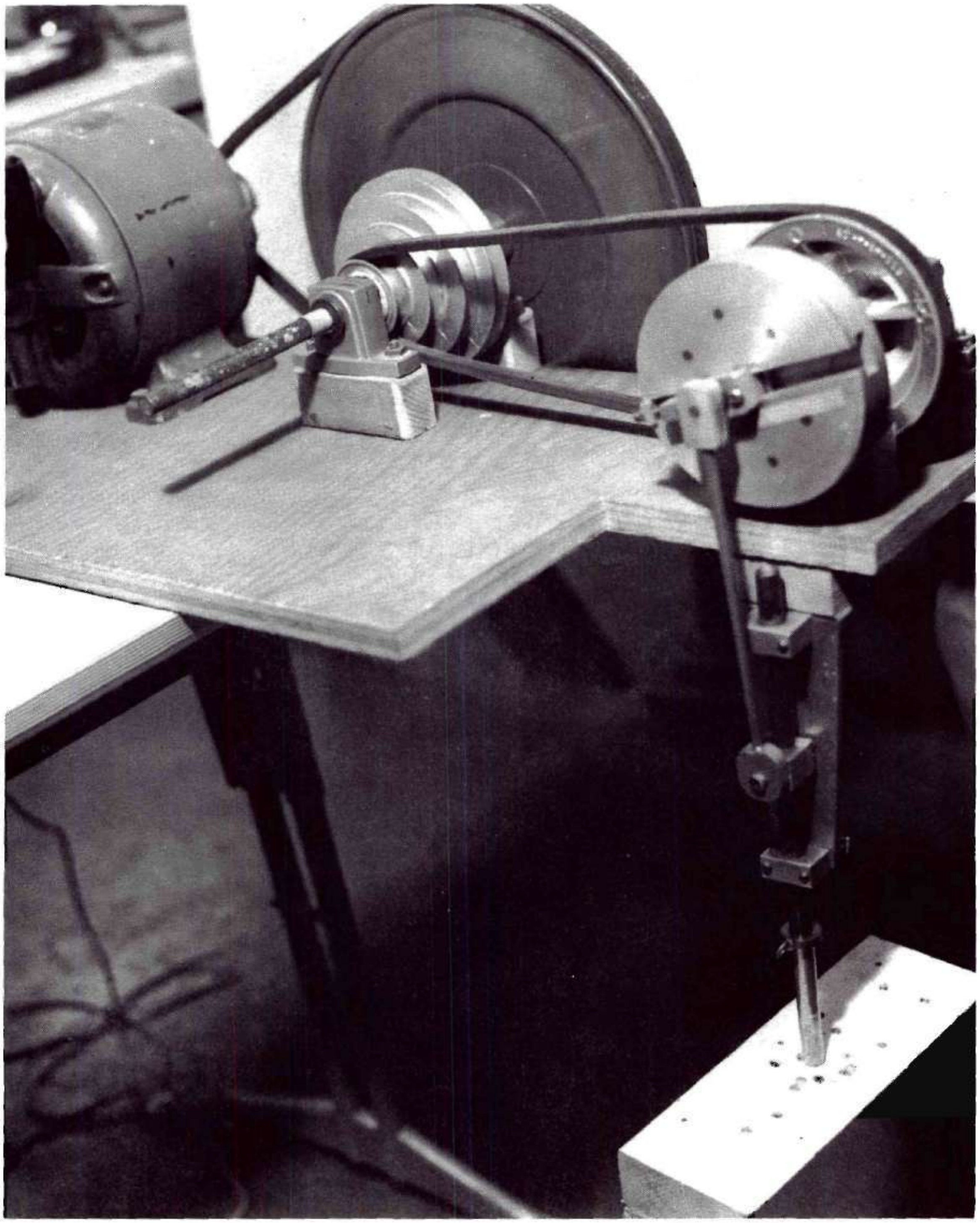
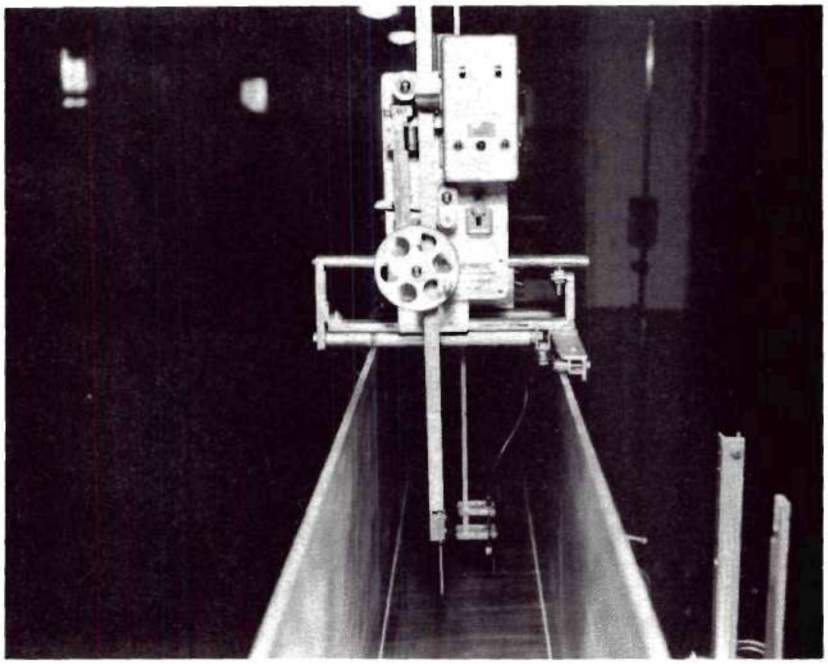
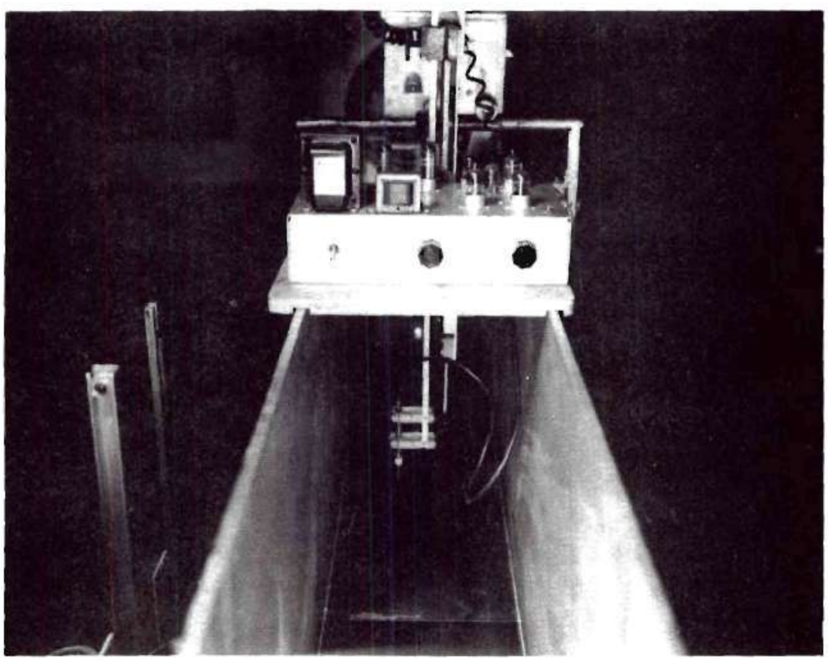


Figure 8. Wave Generator.



(a) Point Gage



(b) Capacitance Gage

Figure 9. Apparatus for Water-Surface Measurements.

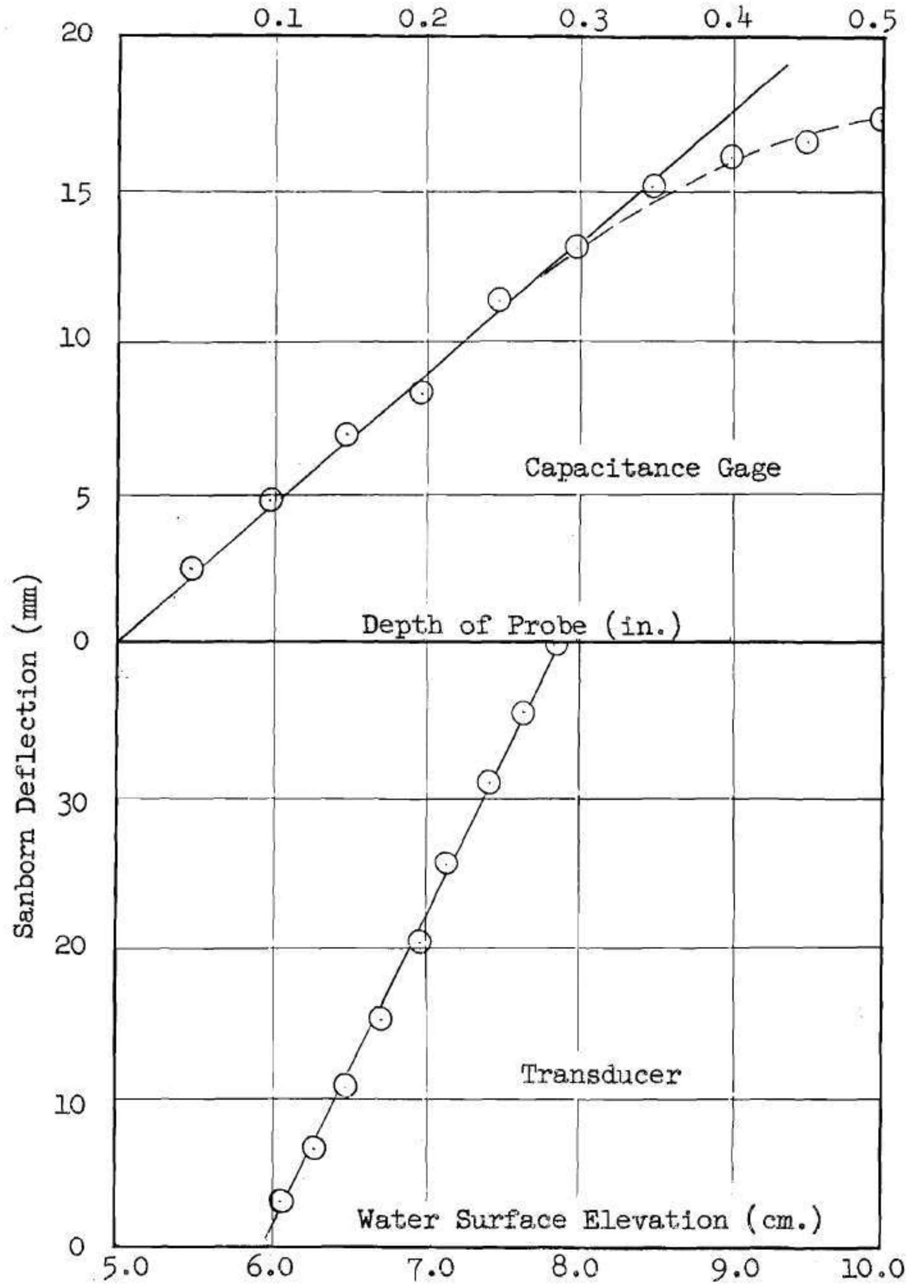


Fig. 10. Calibration Curves

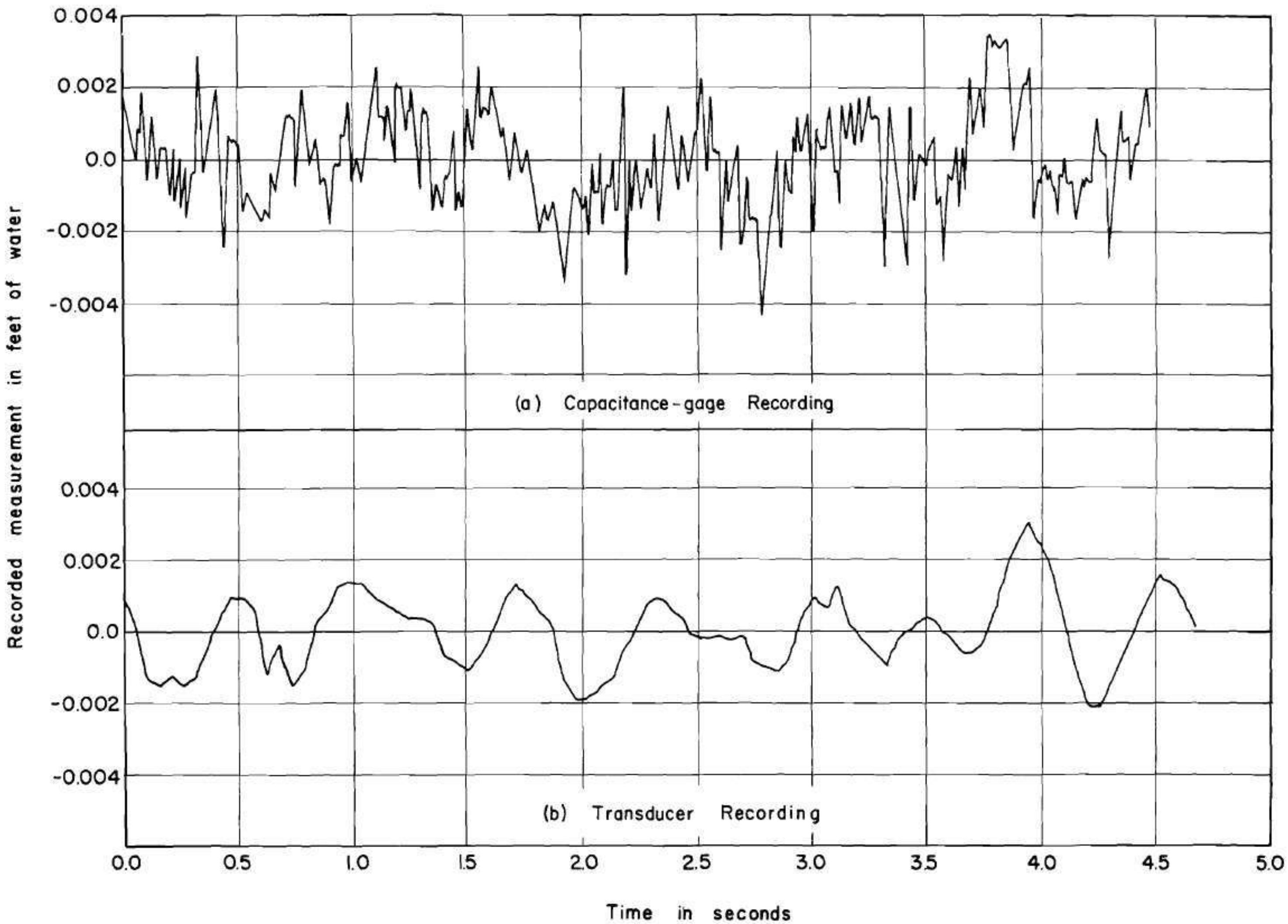


Figure 11. Typical Simultaneous Water-Surface and Piezometer-Head Recordings.

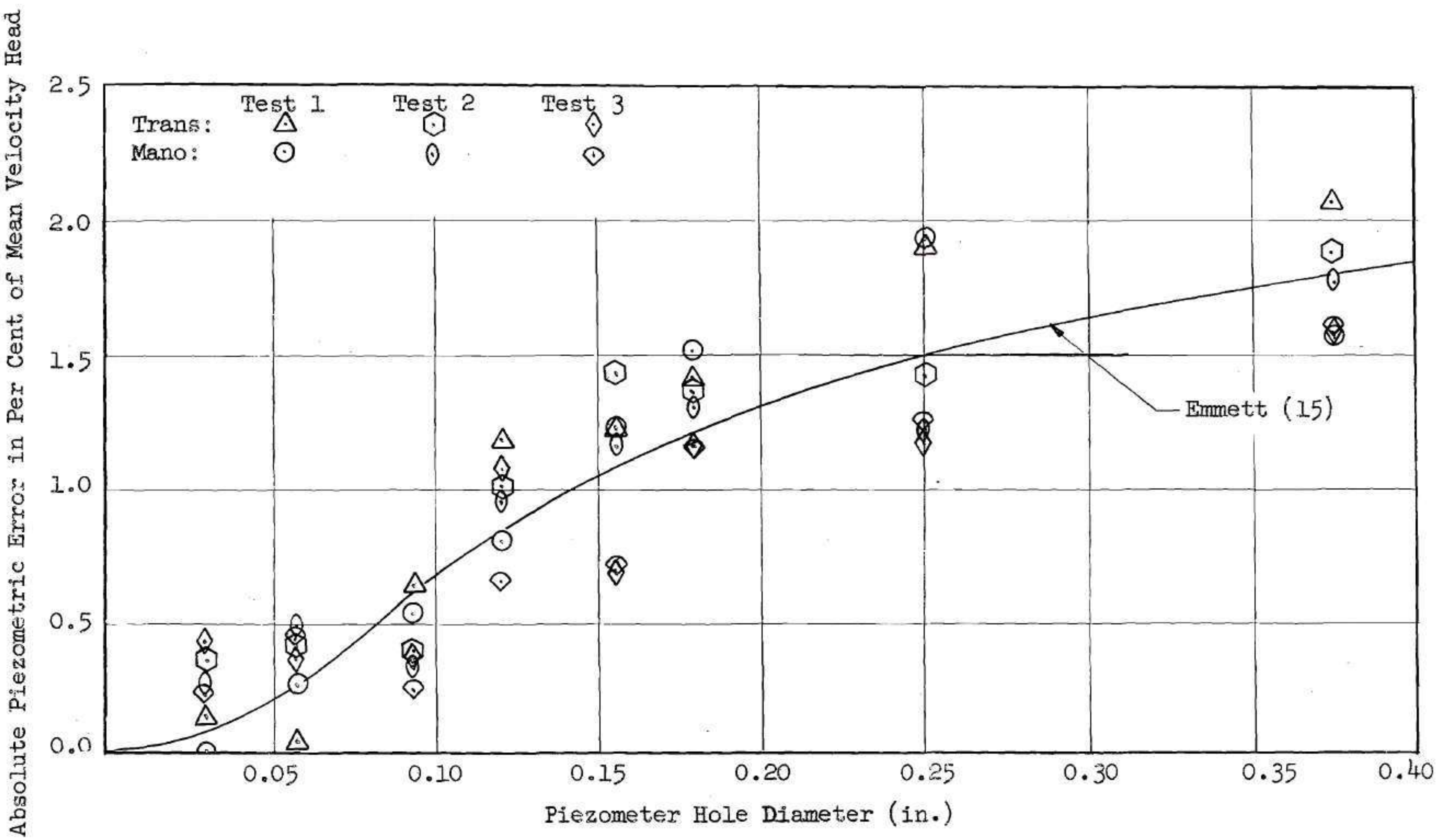


Fig. 12. Summary of Smooth Channel Data

Emmett's Data		Writer's Data	
Test 12	Test 14	Test 3	Test 2
D = 0.1485	D = 0.1410	D = 0.299	D = 0.277
V = 6.90	V = 7.45	V = 6.95	V = 7.88

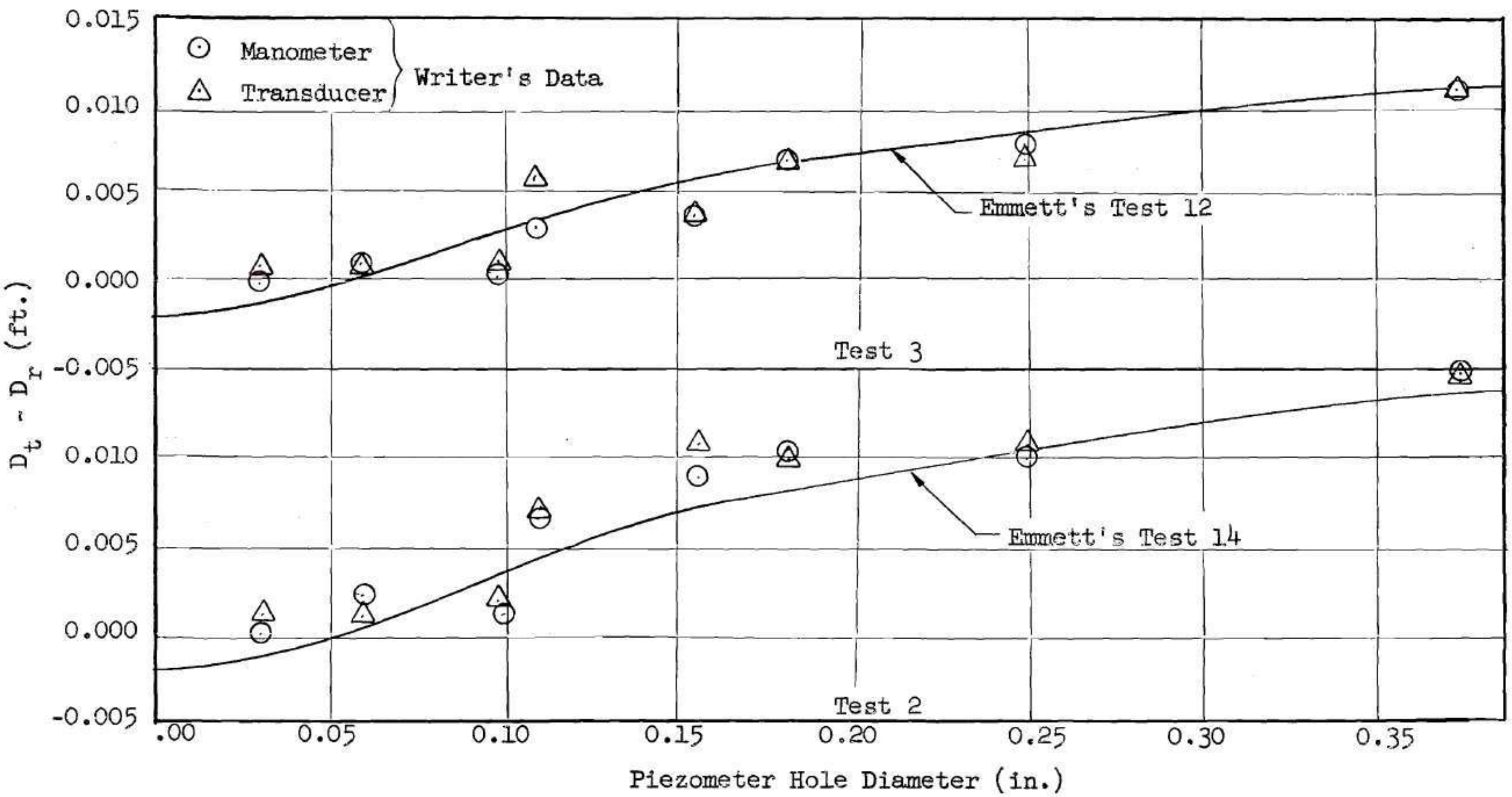


Fig. 13. Effect of Flow Depth on Depth Measurements

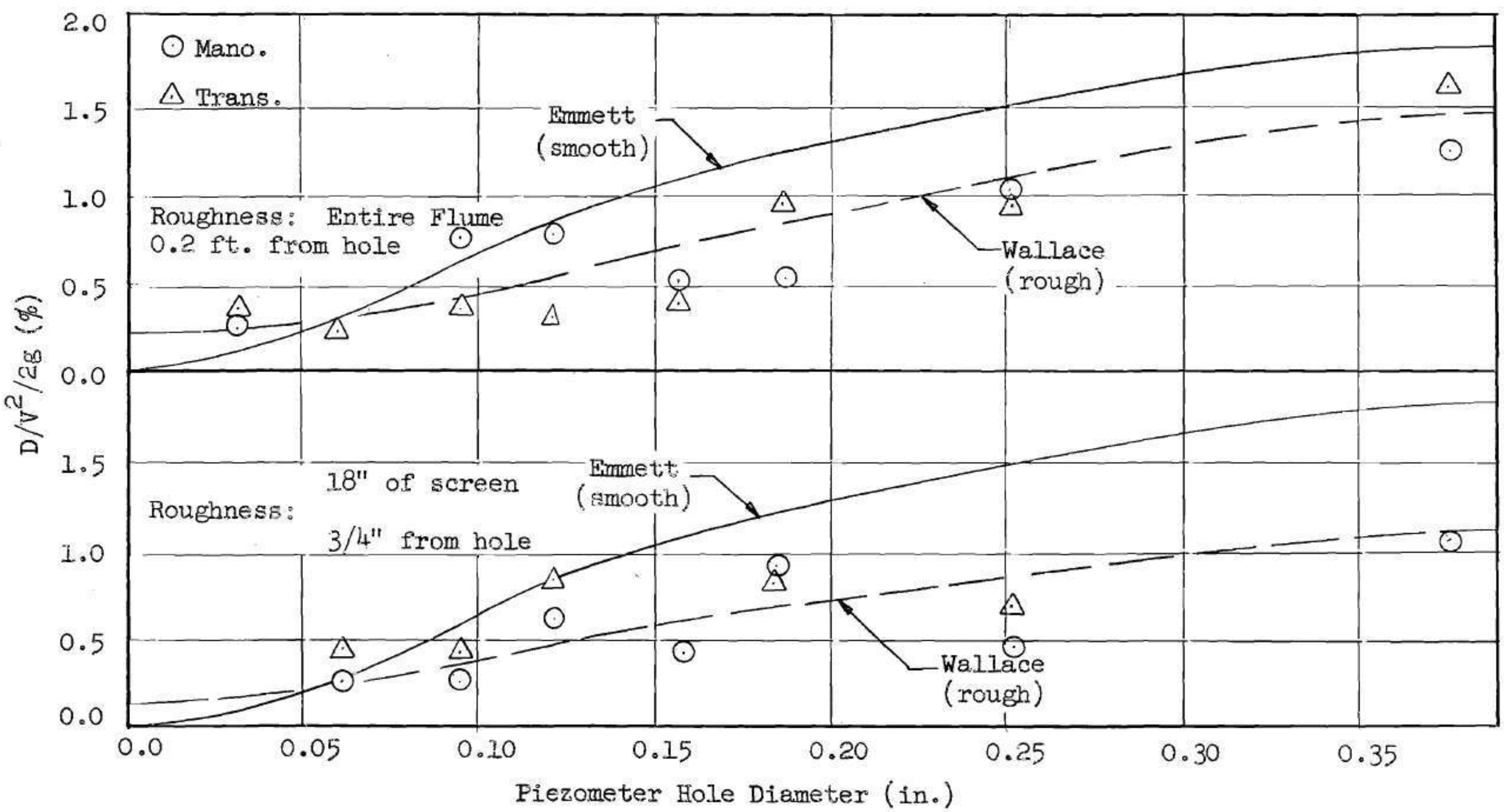


Fig. 14. Effect of Channel Roughness on Depth Measurements

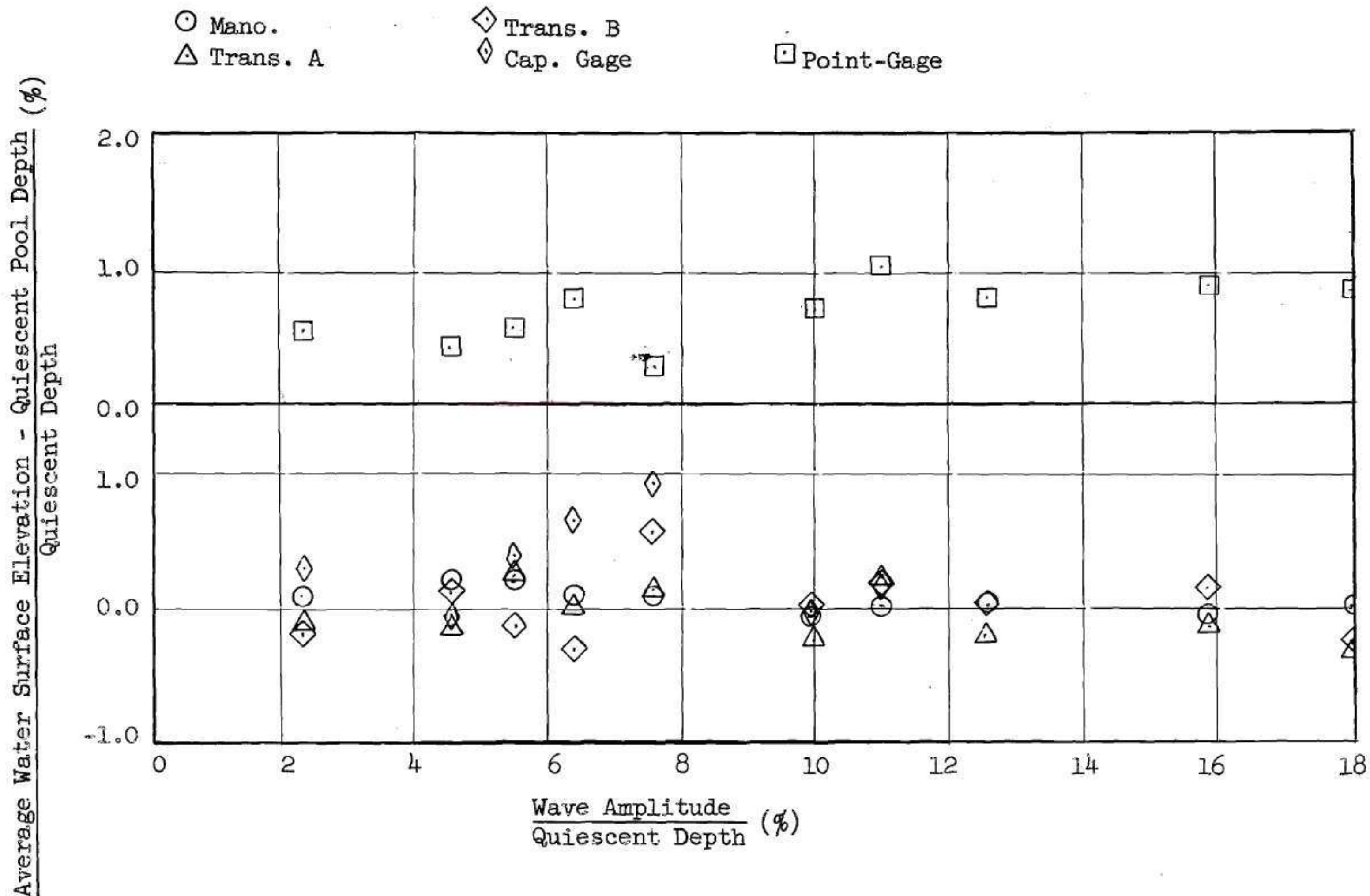


Fig. 15. Effect of Wave Amplitude on Depth Measurements

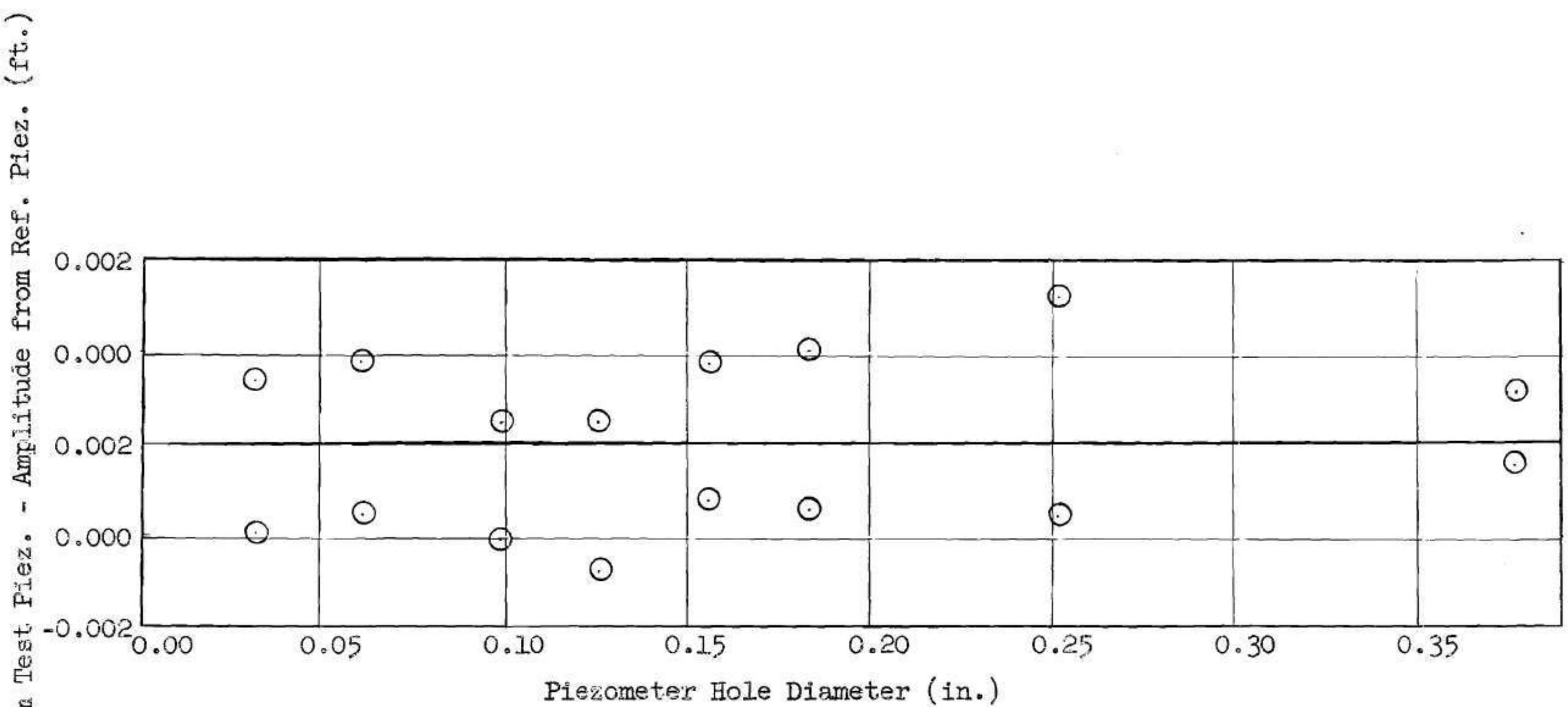


Fig. 16. Effect of Hole Size on Wave Amplitude Measurements

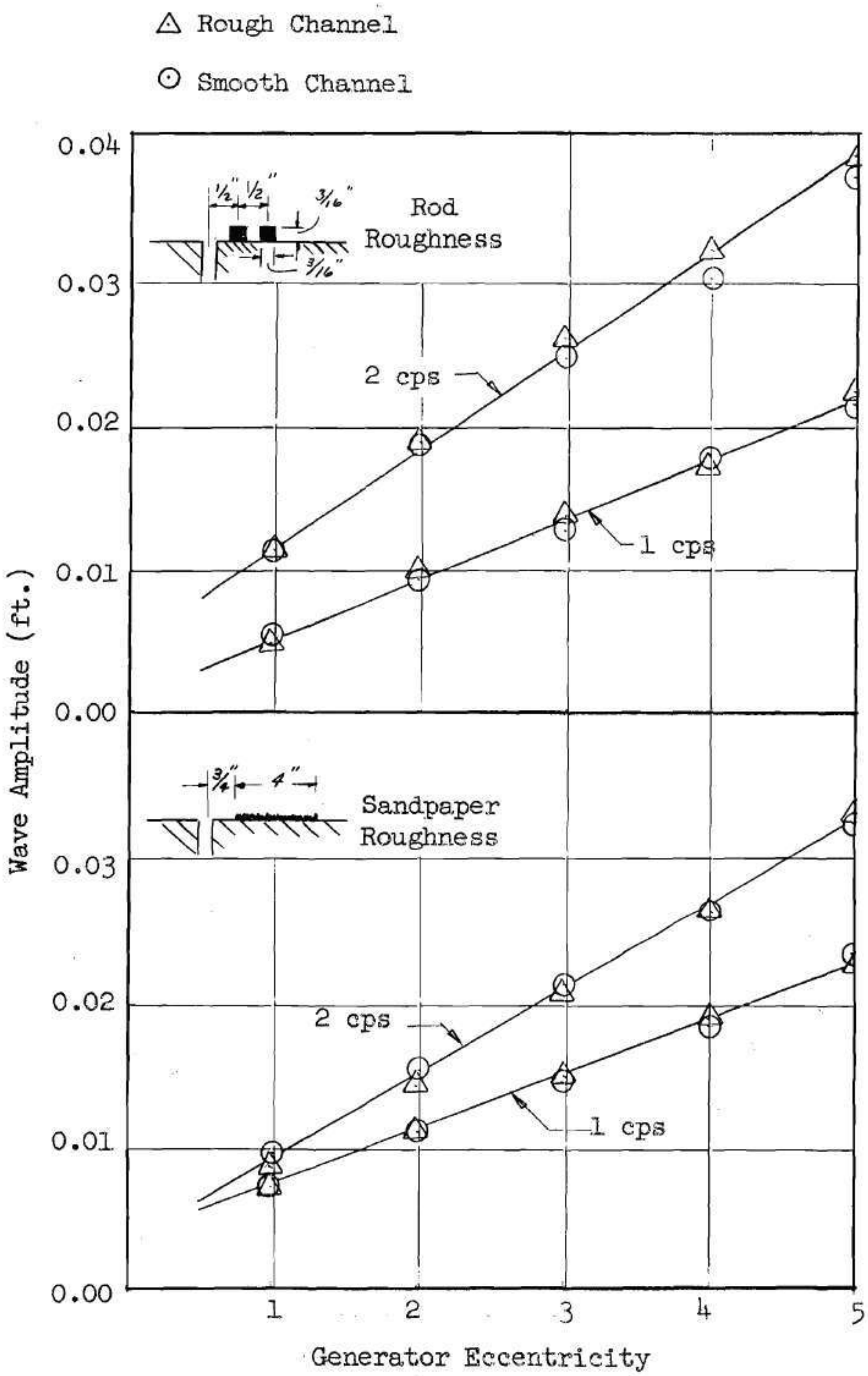


Fig. 17. Effect of Roughnesses on Wave Amplitude Measurements

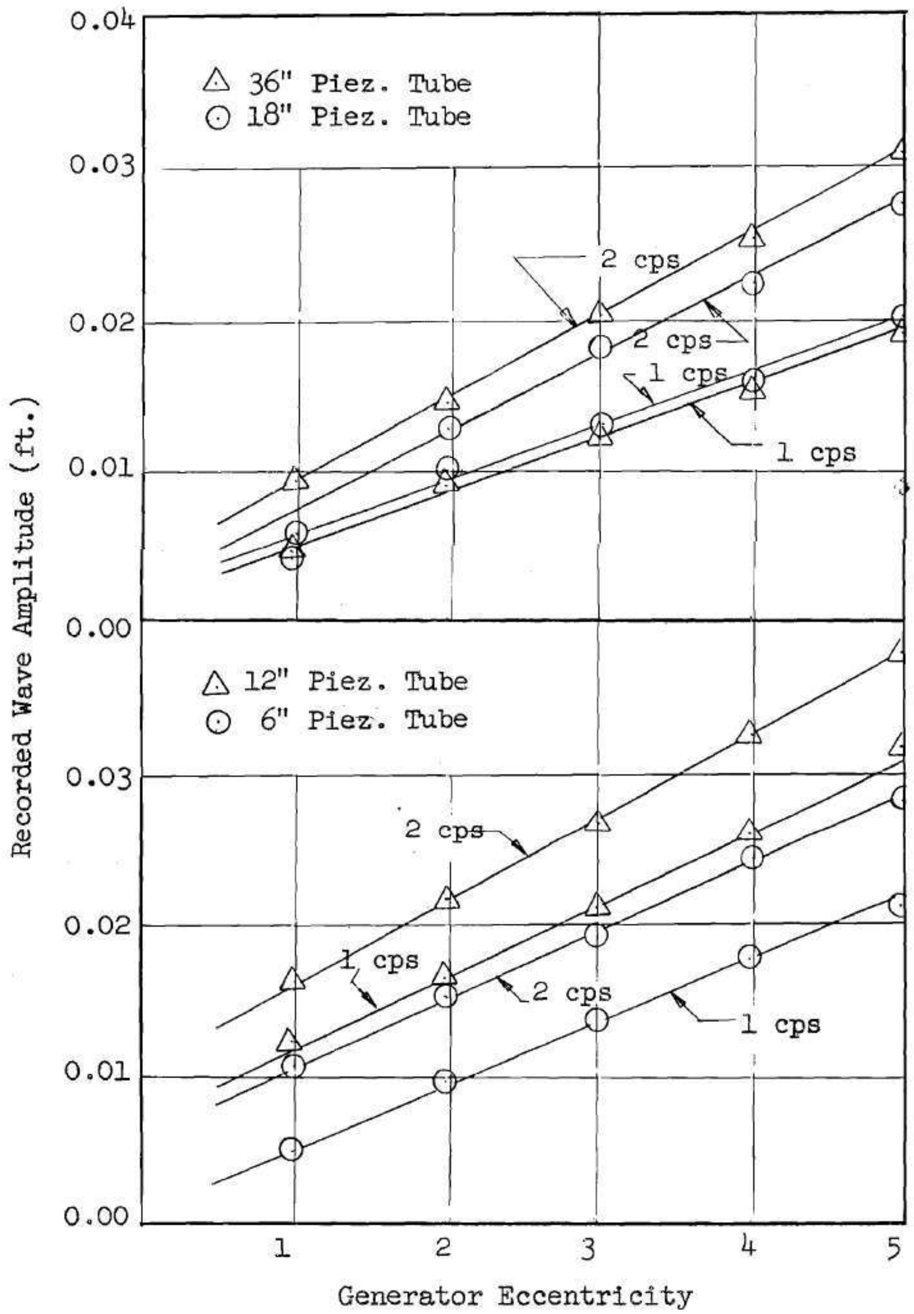


Fig. 18. Effect of Tube Length on Wave Amplitude Measurements

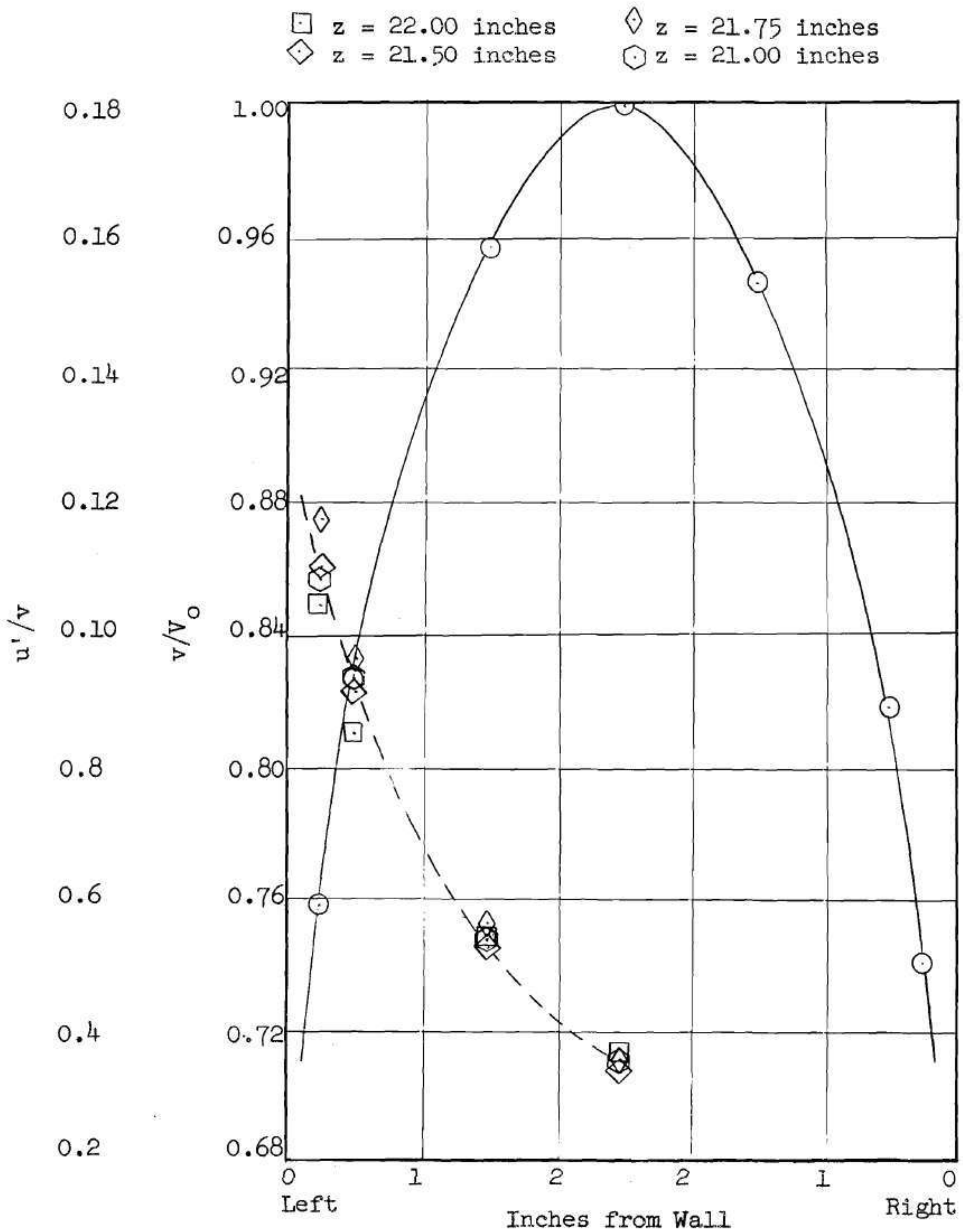


Fig. 19. Velocity Distribution in Wind Tunnel

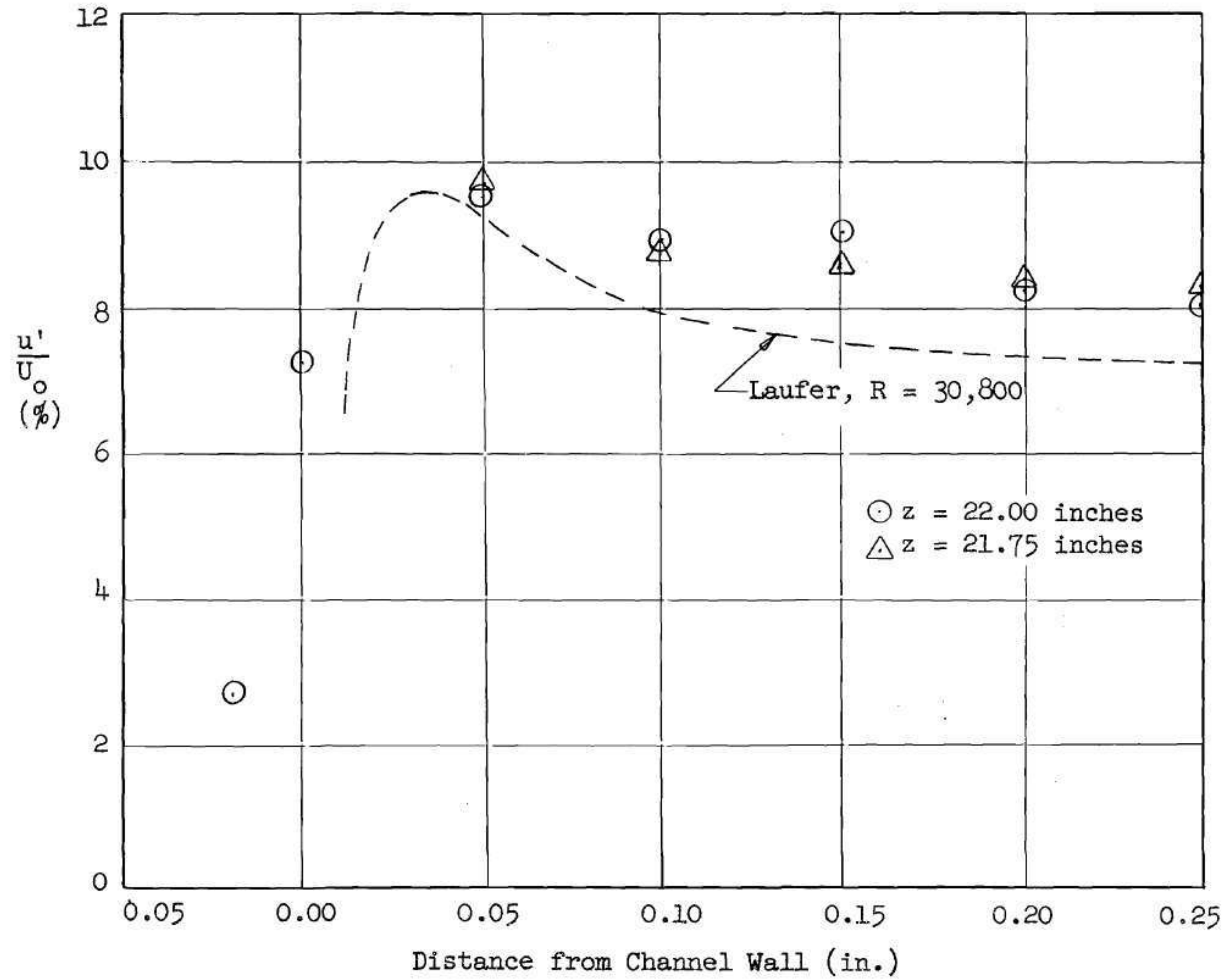


Fig. 20. Turbulence Intensity Near a Piezometer

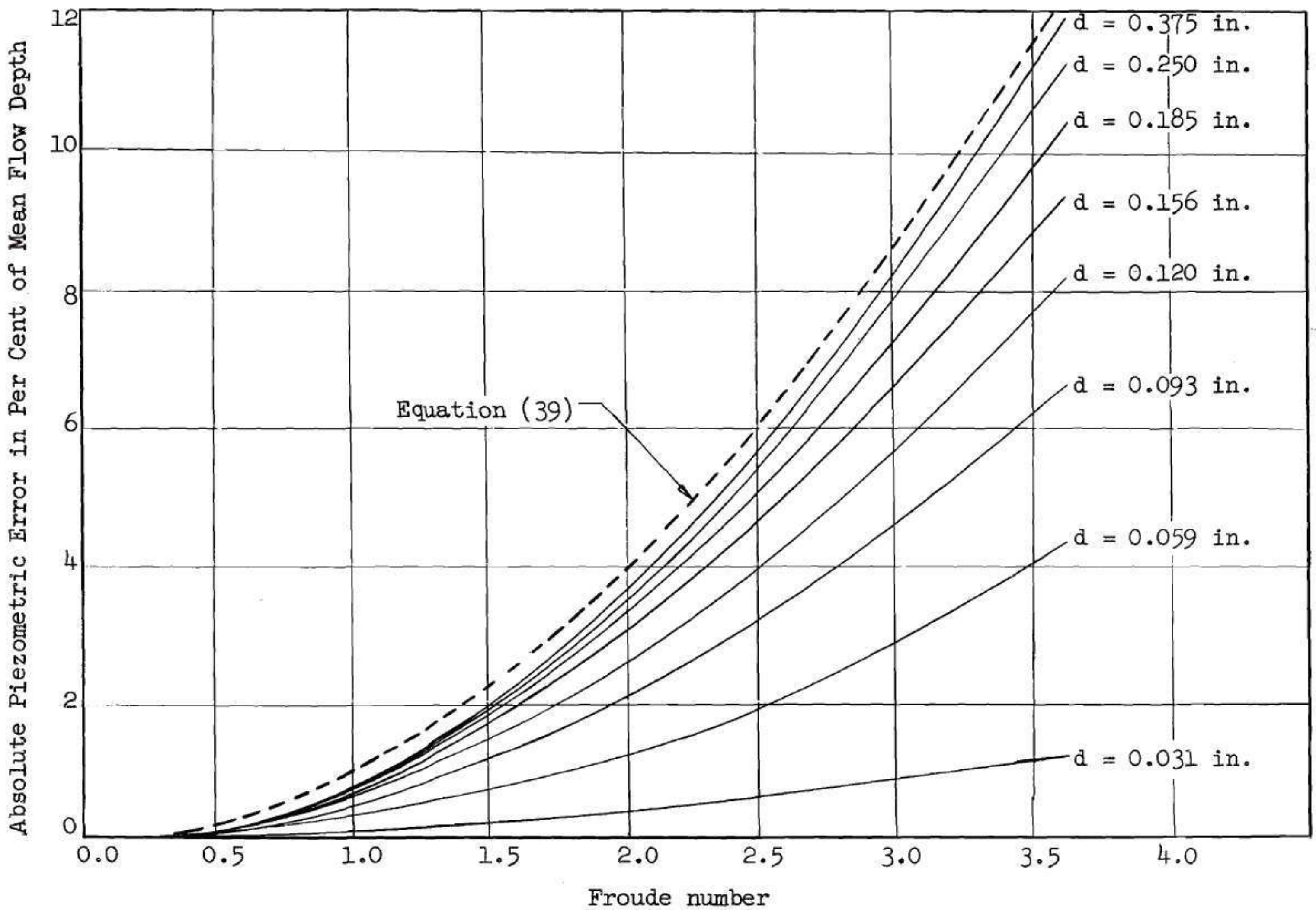


Fig. 21. Summary of Open Channel Data

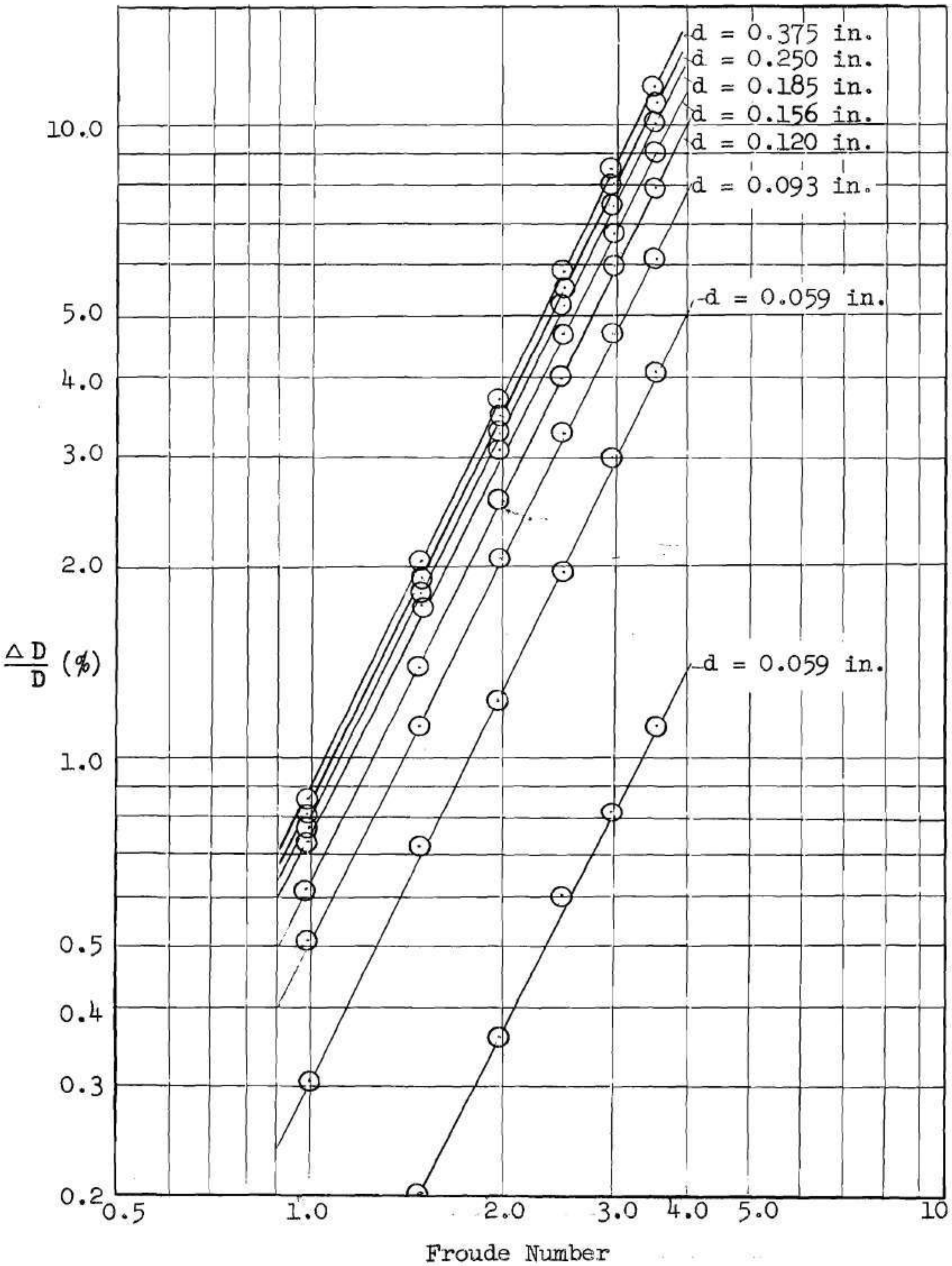


Fig. 22. Summary of Open Channel Data, Log-Log Plot of Fig. 21

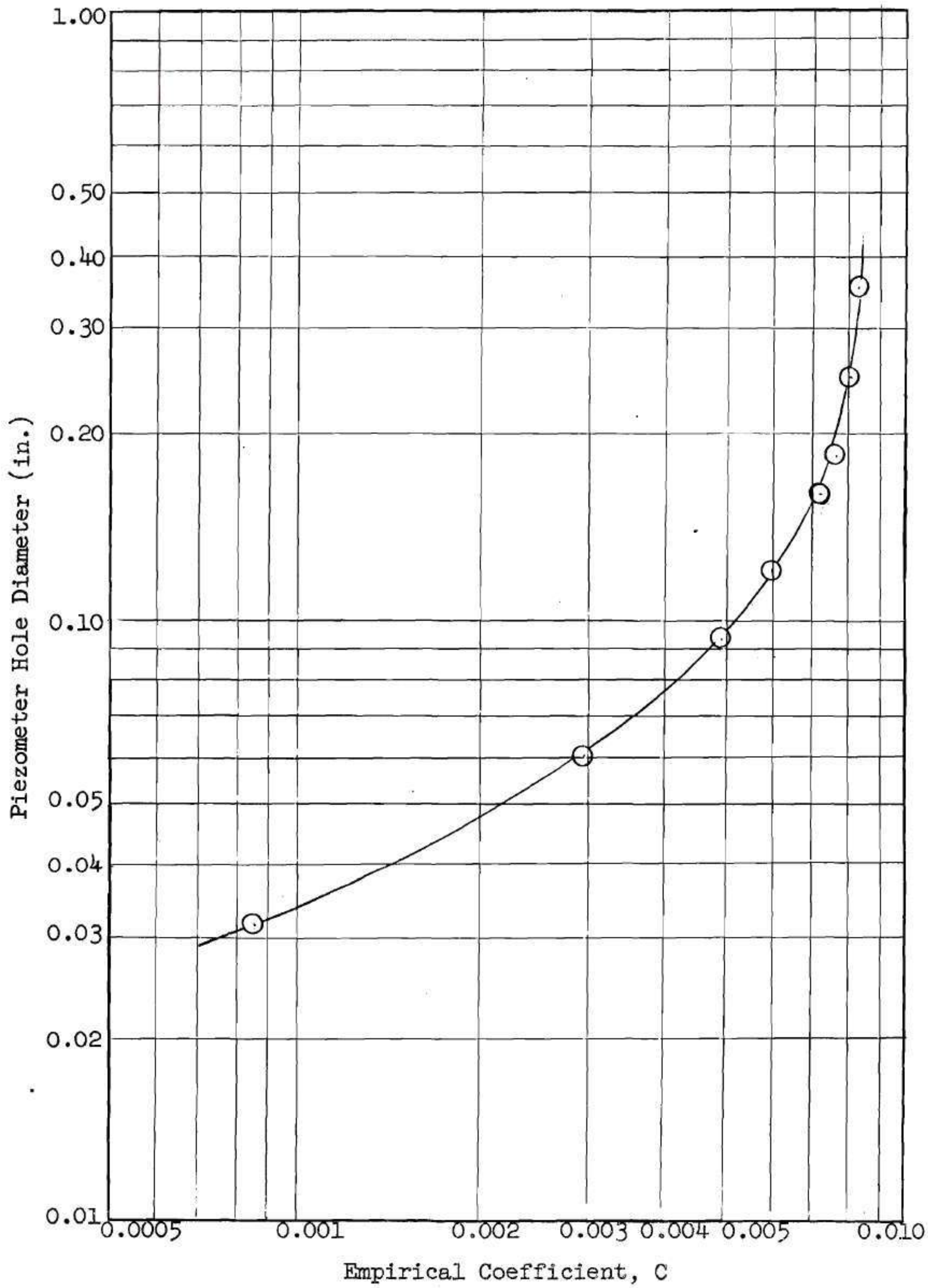


Fig. 23. Effect of Hole Size on Error Coefficient

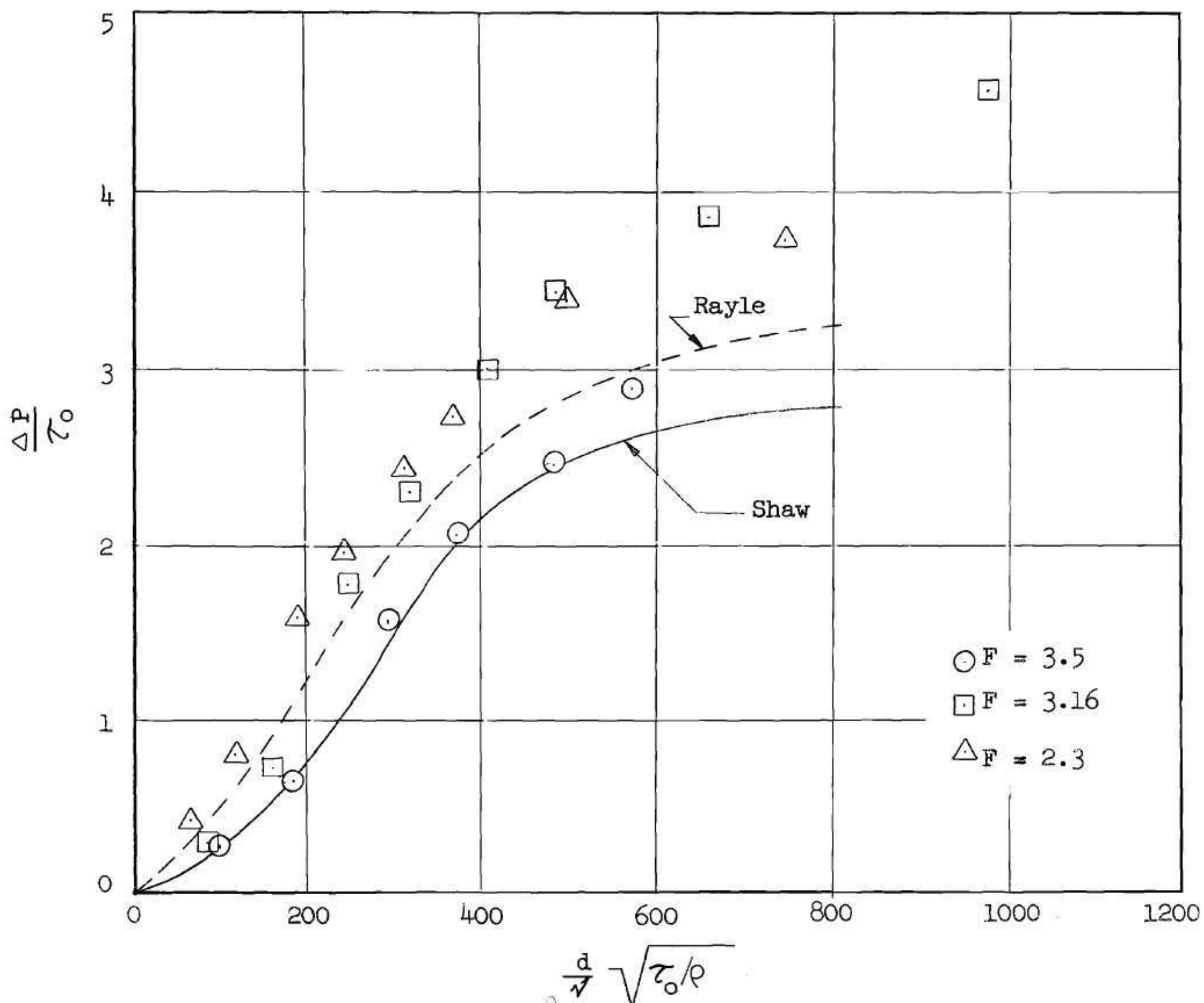


Fig. 24. Comparison with Previous Data, Part (a)

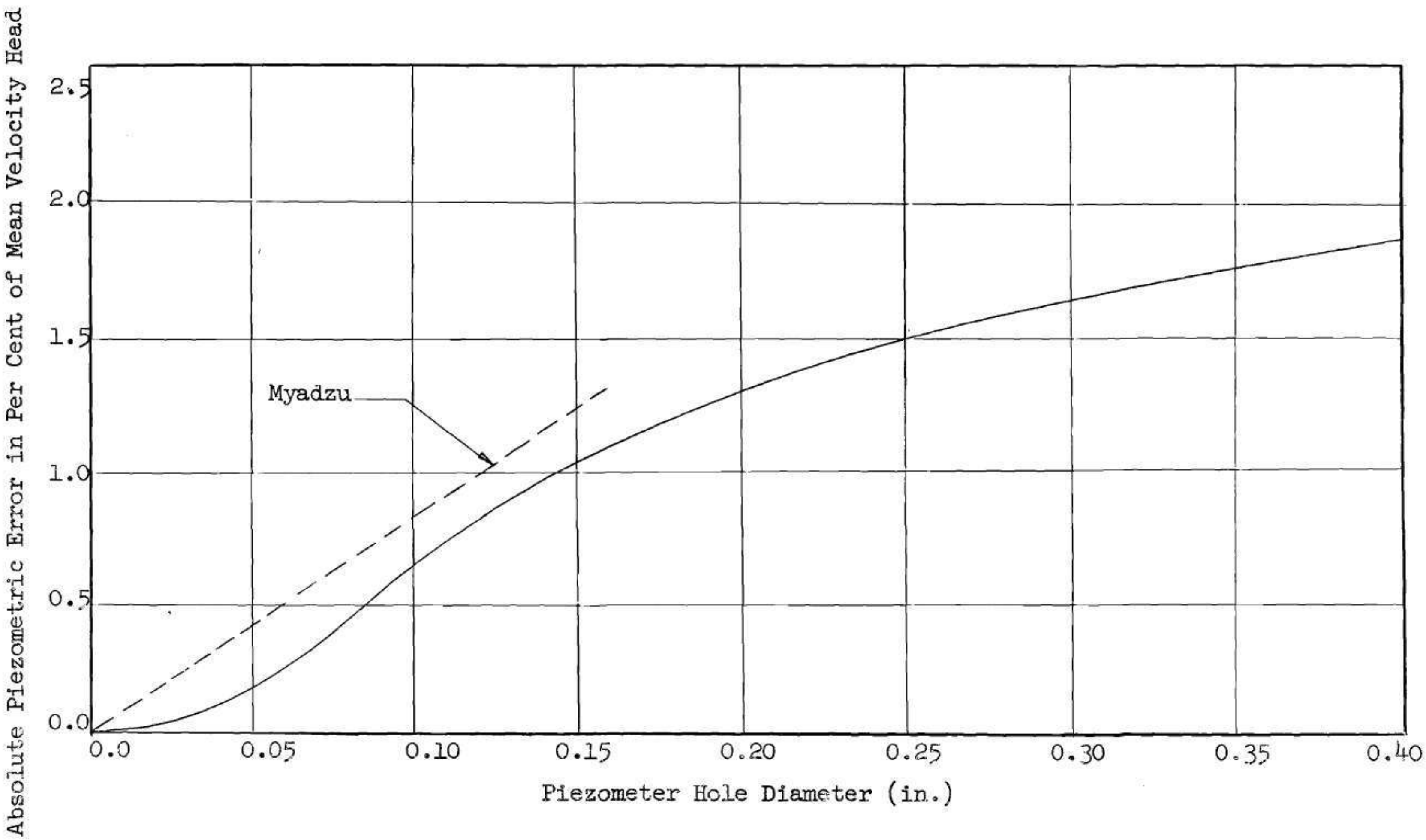


Fig. 25. Comparison with Previous Results, Part (b)

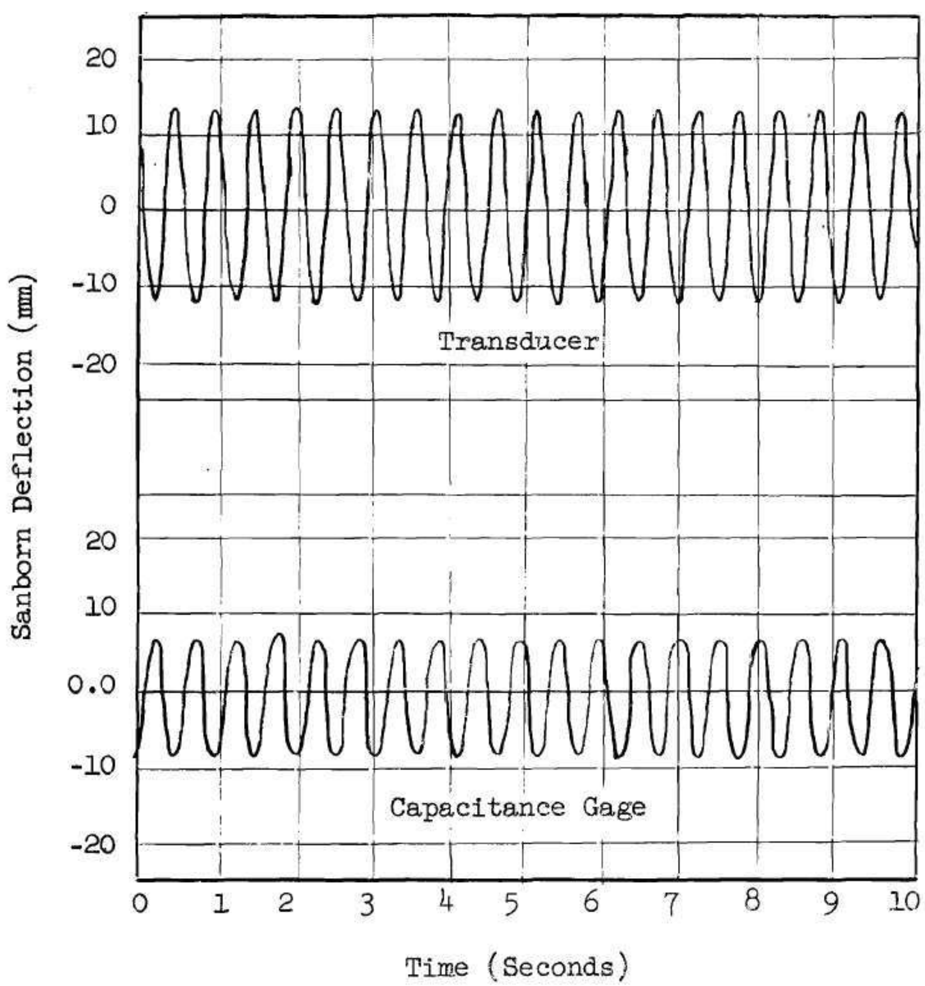


Fig. 26. Typical Surface Wave Patterns

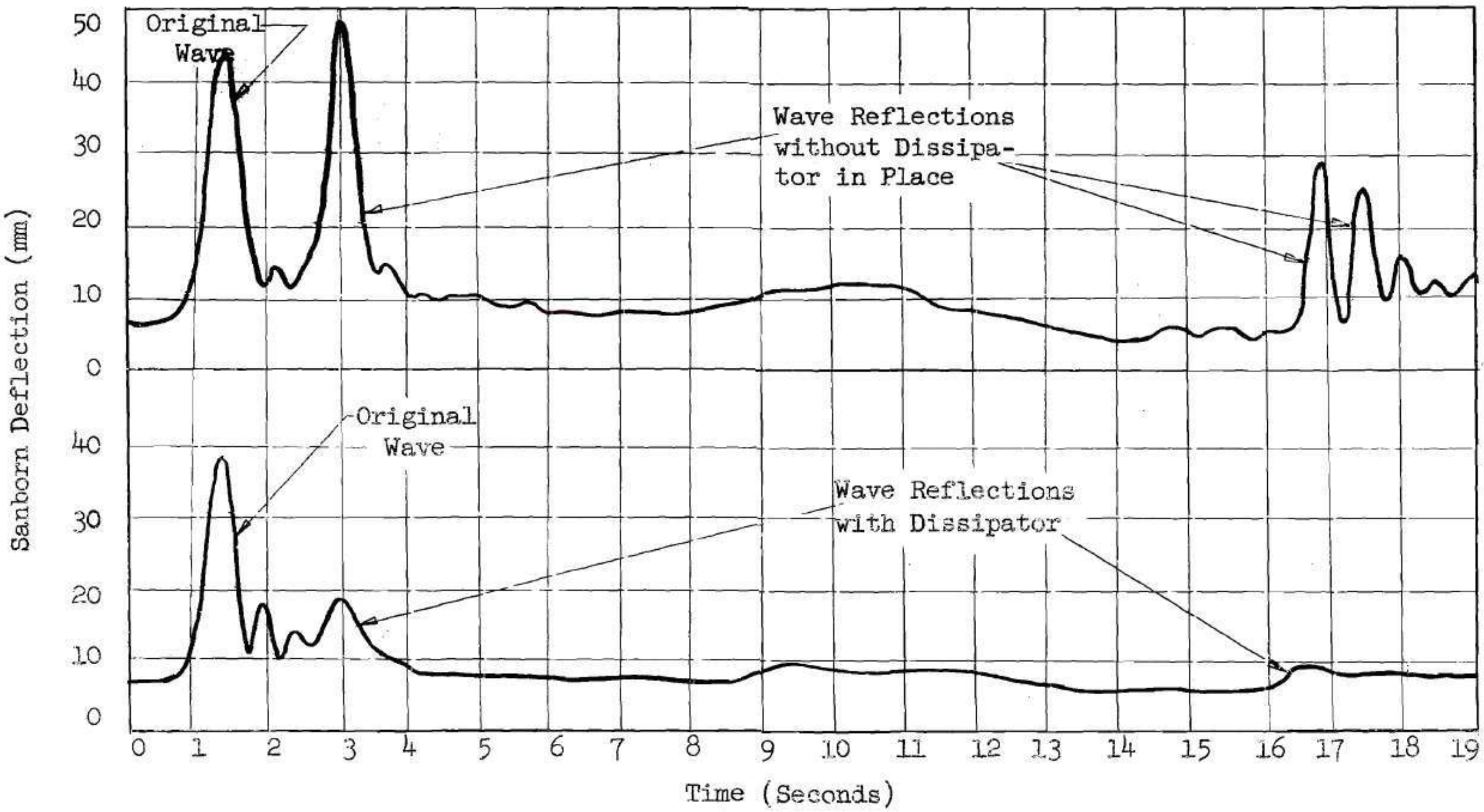


Fig. 27. Effect of Wave Dissipator

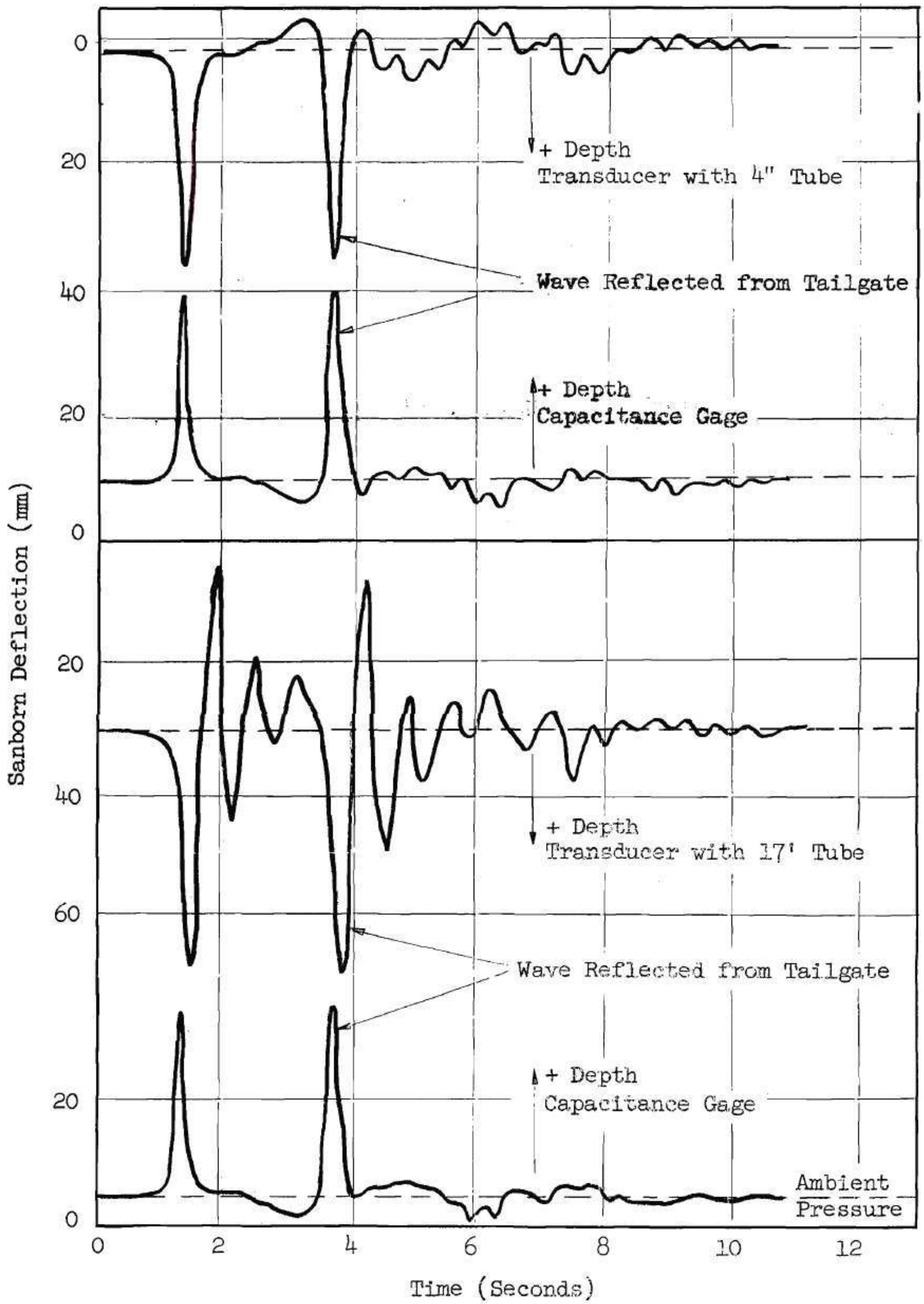


Fig. 28. Secondary Oscillations in Piezometer Tubes

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